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# GILLHAM DAM OUTLET WORKS TOWER HYDRAULIC PROTOTYPE STUDY GILLHAM LAKE, ARKANSAS

by

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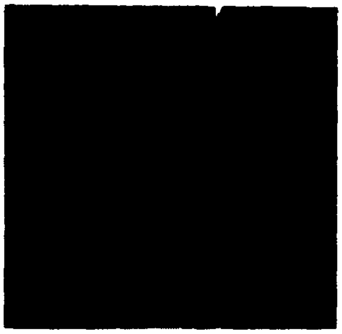



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**13. ABSTRACT** *(Maximum 200 words)*

In October 1984, severe vibrations of the outlet works gate tower of Gillham Dam, southwestern Arkansas, were observed by US Army Corps of Engineers project personnel. The reservoir elevation was about 50 ft above conservation pool when this occurred.

Prototype tests were conducted to determine the severity and cause of vibrations of the intake tower at Gillham Dam. The test program measured the vibrations at the intake tower, wet well, and both service gates; sluice pressures upstream and downstream of each service gate; and the air demand through both air vents.

The vibration data recorded on the intake tower and the wet well showed a predominant frequency of 4 cps. This correlates with the upstream pressure fluctuations measured. The tests in which motion was most severe occurred when gate 1 was at an opening of 4.8 ft or higher. A tapping noise heard off the

(Continued)

**14. SUBJECT TERMS**

| | | |
|---|---|---|
| Accelerometer | Frequency | Velocity |
| Bulkhead slots | Intake tower | Vibration |
| Discharge | Sluice pressures | Wet well |

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upstream side of the intake tower was determined to be the bulkhead slot covers of gate 1 bouncing up and down at a 4-cps frequency. Cross-spectral density plots indicate a relationship between the upstream pressure fluctuations and the intake tower and wet well vibrations at a 4-cps frequency. The pressure fluctuations are approximately five times the pressure fluctuations considered normal for turbulent flow and therefore seem to be the driving force of the intake tower and wet well vibrations. Neither the air vent system, which provides sufficient air into the conduits, nor the downstream pressure fluctuations are a cause of the structure vibrations.

# PREFACE

The prototype tests described in this report were conducted during June 1990 by the US Army Engineer Waterways Experiment Station (WES) under the sponsorship of the US Army Engineer District, Little Rock.

Tests were conducted under the general supervision of Messrs. F. A. Herrmann, Jr., Director of the Hydraulics Laboratory; R. A. Sager, Assistant Director of the Hydraulics Laboratory; and G. A. Pickering, Chief of the Hydraulic Structures Division, Hydraulics Laboratory. This report was prepared by Ms. D. C. McVan with assistance from Mr. R. G. McGee, both of the Hydraulic Analysis Branch, Hydraulic Structures Division, under the supervision of Dr. B. J. Brown, Chief of the Hydraulic Analysis Branch. Instrumentation support was obtained from Messrs. J. C. Ables and S. W. Guy, Instrumentation Services Division, WES.

Acknowledgment is made to Mr. V. P. Chiarito, Structures Laboratory, WES, for structural analysis support, and to individuals of the Little Rock District for their assistance in the investigation.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

CONTENTS

## CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| acre-feet | 1233.489 | cubic metres |
| cubic feet | 0.02831685 | cubic metres |
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048 | metres |
| feet per second | 0.3048 | metres per second |
| inches | 2.54 | centimetres |
| miles (US statute) | 1.609344 | kilometers |
| pounds (mass) per square inch | 6894.757 | pascals |

# GILLHAM DAM OUTLET WORKS TOWER HYDRAULIC PROTOTYPE STUDY
# GILLHAM LAKE, ARKANSAS

## PART I: INTRODUCTION

### Pertinent Features of the Project

1. Gillham Dam (Figure 1) is located on the Cossatot River in southwestern Arkansas, 49.0 river miles* upstream from the confluence with the Little River and approximately 17 miles north of DeQueen, Arkansas (Figure 2). The multiple purpose project provides water supply, flood control, water quality control, and fish and wildlife conservation to the area.

2. The main embankment is a rock fill structure with an impervious

Figure 1. Gillham Dam and Reservoir

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

earth core. At the top of the dam, el 586.0*, the embankment is 1,750 ft long. The structure impounds 33,030 acre-ft of water at conservation pool el 502.0.

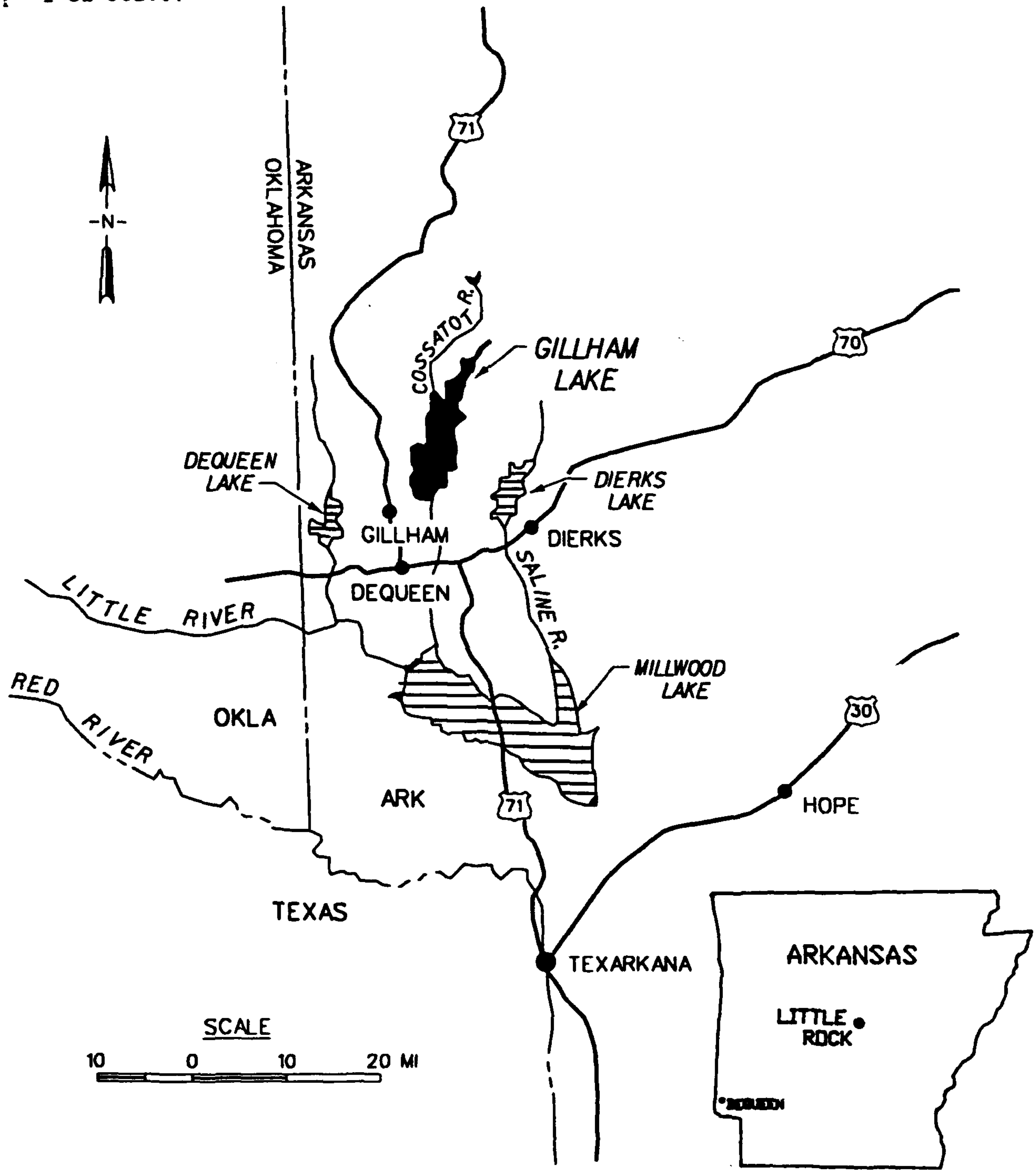


Figure 2. Location and vicinity map

* All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

## Spillway and Outlet Works

3. The spillway is a gated concrete gravity ogee weir located about 1,500 ft west of the main embankment. The structure provides a clear opening of 200 ft controlled by four 50-ft-wide by 42-ft-high tainter gates. The crest is at el 527.0 with a sloping apron extending downstream about 200 ft, terminating at a flip bucket.

4. The outlet works consist of two 4.5-ft-wide by 10.0-ft-high conduits that transition into a 10-ft-diam conduit, 625 ft long with the invert at el 437.0. Flows are controlled by two 4.5-ft-wide by 10.0-ft-high hydraulically operated slide gates. Low-flow releases are normally made through a 30-in. low-flow pipe which conveys flow from the multilevel wet well. This flow is controlled by a butterfly valve and empties into the outlet conduit just downstream of service gate 2 through the 24-in.-diam air vent. The invert elevations of the wet well intakes are 472.0 and 487.0. There are 24-in.-diam air vents downstream from each service gate.

## Purpose and Scope of Tests

### Background

5. In October 1984, severe vibrations of the Gillham Dam outlet works gate tower were observed by Corps of Engineers project personnel. The reservoir elevation was about 50 ft above conservation pool when this occurred. Several investigation teams visited the site to study various operation features and structural behavior for possible vibration causes and structural problems. The procedures, findings, and recommendations of the investigations are given in a summary prepared by the US Army Engineer District, Little Rock (reference "Gillham Dam Inspection Summary," SWLED-HW 1985).

6. The investigating team found that vibrations increased when the low-flow valve was opened during service gate releases and recommended termination of combined releases of this type. Service gate openings were then determined which could be used to release flow without creating serious structural vibrations until the actual cause and subsequent solution to the vibration problems were determined. In addition, a prototype test program designed to determine the cause of the vibrations at Gillham was recommended. The Little Rock District requested that the US Army Engineer Waterways

Experiment Station (WES) propose a prototype test program (reference Mr. E. D. Hart's Memorandum for Record, WESHP-P, dated 12 March 1985).

7. In the recent past, project personnel have observed vibrations in the gate tower during conditions that normally have not produced any movement of the gate tower. The tower was vibrating at lower pool elevations (512.0 and 514.0 ft) and lower discharges. It was also vibrating at gate settings that in the past were considered "safe."

## Purpose

8. The primary purpose of the test program was to assess the vibrations occurring at the intake tower, wet well, and sluice gates for a full range of gate openings under the maximum available head. In addition, it was desired to determine if a correlation existed between these vibrations and sluice pressure fluctuations and/or air vent velocity changes. The WES test program included measurement of (a) vibrations at the intake tower, wet well, and both service gates, (b) sluice pressures upstream and downstream of each service gate, and (c) air demand through both air vents. An additional pressure measurement was taken to measure changes in the water-surface elevations during testing.

## Scope

9. Five series of tests (A, D, F, I, and B), each performed under different flow conditions, were conducted at Gillham Dam during 2-9 June 1990. Series A was conducted with service gate 2 open and service gate 1 and the low-flow valve closed; Series D was conducted with service gate 1 open and service gate 2 and the low-flow valve closed; Series F was conducted with both service gates open at balanced gate settings and the low-flow valve closed; Series I was conducted with both service gates open at unbalanced gate settings and the low-flow valve closed; and Series B was conducted with both service gates open at balanced gate settings and the low-flow valve open. Each series covered the full range gate openings from 3- to 4-ft and at 0.2-ft increments from 4.6 to 5.6 ft at an average pool elevation of 543.30. Both air vents remained open during the entire testing program. Table 1 is a list of the test schedule and comments.

## PART II: TEST FACILITIES, EQUIPMENT, AND PROCEDURES

### Test Facilities

10. Locations of the test instrumentation are shown in Plates 1 and 2, and the specifics of each transducer are listed in Table 2.

#### Structure and gate vibrations

11. Structure vibrations were measured with two clusters of three accelerometers measuring accelerations in the vertical, transverse, and parallel directions to flow. The first cluster (TAV, TAT, and TAP) was epoxied to the roof of the intake tower at el 586.0. The second cluster (WAV, WAT, and WAP), housed in a waterproof canister, was epoxied to the roof of the wet well at el 529.8 (Plate 2). The wet well accelerometers were previously installed 24-26 February 1985 to anticipate the higher pool elevations during testing. A special accelerometer plate was welded to the skinplate on the downstream side of each service gate and an identical cluster for each gate (GAV1, GAT1, GAP1 and GAV2, GAT2 and GAP2), housed in a waterproof canister, was attached to the plates (Plate 1). Additional vertical accelerometers (GV1 and GV2) were installed on the staff gage of each service gate (Plate 2) during testing. This was to provide backup measurement of the vertical movement of the service gates in case the gate accelerometers should fail. Figure 3 shows the accelerometer clusters on the intake tower and wet well roofs, and Figure 4 shows the clusters on the service gate and staff gage.

#### Sluice pressures

12. Static and dynamic pressures upstream and downstream of each service gate were measured with absolute pressure transducers, PUS1, PDS1, PUS2, and PDS2. The upstream transducers were installed in manhole covers located between the emergency and service gates at el 447.0, and the downstream transducers were installed in plates that were placed across each air vent outlet at el 447.0 (Plate 2). Figure 5 shows the placement of the upstream and downstream pressure transducers.

13. The transducer cables downstream of the service gates passed through their respective air vent and exited through a 1-3/8-in. cable pull hole cut in each air vent at el 486.0. The cables were then passed up through the equipment shaft to the top of the intake tower to the recording station.

a. Accelerometers attached to roof of intake tower at el 586.0

b. Accelerometer canister attached to roof of wet well at el 529.8

Figure 3. Accelerometer clusters on the intake tower and wet well roofs

a. Vertical accelerometers attached to staff gage

b. Accelerometer canister attached to service gate

Figure 4. Accelerometer clusters on the service gate and staff gage

a. Upstream pressure transducer, PUS, installed in manhole cover at el 447.0

b. Downstream pressure transducer, PDS, installed in strut across the air vent at el 447.0

Figure 5. Pressure transducers upstream and downstream of service gates

Air velocities

14. A 2-in. pipe modified to house 4 pitot tubes (AV1A, AV1B, AV1C, and AV1D) was installed in air vent 1 at el 484.0 (Plate 1). A single pitot tube (AV2) was installed in air vent 2 (Plate 2). The pitot tubes were placed facing upstream for measuring the air flow velocity in the conduits. The static and stagnation ports of each pitot tube were connected to electronic differential pressure transducers to measure the pressure differential. Figure 6 shows the four differential pressure transducers at air vent 1.

Figure 6. Differential pressure cells for air vent 1 at el 484.0

## Other Measurements

15. Other recorded data consisted of reservoir water-surface elevation, air temperature, gate opening, and water discharge. These data were provided by the project and District personnel. Water discharge was determined from computed discharge rating curves provided by the Little Rock District.

## Test Equipment

16. The test equipment listed and described herein includes the

transducers, cables, and recording equipment. Transducers used in the tests were as follows:

a. Vibrations: 1 $\mu$g to 25 g servo-accelerometers.

b. Sluice pressures: 100 psia (PUS) and 50 psia (PDS) pressure transducers.

c. Air velocity (pitot tube pressure differential): 0.125 psid to 0.50 psid pressure transducers.

17. Cable lengths required for the test program were determined from contract drawings and actual measurements at the project. These cable lengths (Table 2) were cut and used in the calibration of their corresponding transducers to account for line losses.

## Data Acquisition

18. All data were digitally recorded using the Data Acquisition and Reduction System (DARS), a turn-key system built around a Masscomp MC5500 data acquisition system. This provided onsite data verification and analysis. The analog data were also recorded on magnetic tape as a backup with a portion of the data transferred to oscillograms for confirmation. The recording station was housed in an instrumentation truck located on the bridge of the intake tower at el 586.0. Figure 7 shows equipment setup at the recording station. Signal cables from all transducers were connected directly to the DARS.

## Test Procedures

19. Testing began 5 June 1990 at pool el 544.9 and was completed 8 June 1990 at pool el 541.7. The digital data for all transducers were collected simultaneously at a sampling rate of 512 samples/sec. The data for each test were immediately displayed and verified and the time-history statistics generated. Spectrum analysis in the form of Fast Fourier Transforms (FFT) were conducted posttest to assist in preliminary onsite evaluations of the possible driving mechanisms of the vibrations. Each test took approximately two hours to complete. This allowed adequate time for the establishment of possible vibration conditions.

20. The procedure was generally the same for each test series and consisted of the following:

Figure 7. Recording station and equipment

a. Record test number, gate opening, date, time, and conditions.

b. Record step calibrations.

c. Record zero levels.

d. Raise test gates to desired opening; allow flow to stabilize.

e. Record data on the DARS and magnetic tape.

f. Record discharge, pool elevations, and air temperatures.

g. Repeat steps a and d-f for each gate opening.

h. Record post-test step calibrations.

21. Because of the time it took to close the gates (approximately 1-1/2 hr), the step calibrations and zero levels (requiring no flow conditions) were recorded at the beginning of test series A and D only and the post-test step calibrations were recorded at the end of test series B.

22. Voice comments on the tape and field notes were continuously made for later reference. Gain changes and calibrations were made as required during the test period.

# PART III: TEST RESULTS AND ANALYSIS

23. All data channels were recorded and reduced simultaneously providing a direct time-dependent relationship among all channels. All data reduction was accomplished at WES. Representative tests from each test series were chosen and a 1-min sample of each data channel was digitized. A 12-Hz low-pass filter was chosen to preprocess the raw data to eliminate data not related to the forcing mechanism driving the structural vibration. The test conditions for the representative tests are presented in Table 3.

## Structure and Gate Vibrations

24. Three-directional acceleration measurements were made on the roof of the intake tower (TAV, TAT, TAP), wet well (WAV, WAT, WAP), and on the service gates (GAV, GAT, GAP), as shown in Plates 1 and 2. A vertical acceleration measurement was made on the staff gages (GV), as shown in Figure 4. The measurements were made to obtain their magnitudes and frequency of motion at each gate opening and to determine if any correlation existed between the structure, gate vibrations, and conduit pressure fluctuations.

### Intake tower and wet well vibrations

25. A summary of the intake tower and wet well accelerations are presented in Tables 4 and 5. The instantaneous maximum, minimum, and peak-to-peak accelerations and predominate frequencies were determined from the time histories and corresponding FFT's. The sinusoidal structural displacements were estimated by the equation

$$d = \frac{386.4\ (a)}{(2\pi f)^2} \qquad (1)$$

where

d = peak-to-peak sinusoidal displacement, in.

a = greatest peak-to-peak acceleration, g's

f = predominant frequency, cps

The same procedure was used in determining the service gate and staff gage acceleration data.

26. A predominate frequency recorded for both the intake tower and wet well during tests in which motion occurred was 4 cps. This frequency was

predominate in the transverse and parallel directions to flow (TAT, TAP, WAT, and WAP). The range of frequencies for the intake tower was 0.5 to 8.0 cps and for the wet well was 0.5 to 10.0 cps. The frequencies recorded for the wet well were somewhat higher than the intake tower. The accelerations were highest during tests in which gate 1 was at an opening of 4.8 ft or higher. Vibration of the tower was most severe during tests in which gate 1 was at an opening of 5.15 ft. Plate 3 presents graphs of the effects of vibrations as they relate to persons and structures. The accelerations and displacements lie within the region of troublesome to persons and severe to persons. A sample time-history with its corresponding FFT plot for each measured direction is shown in Plates 4 and 5.

27. A tapping/train noise was heard off the upstream side of the intake tower during all tests. This noise was believed to have been the bulkhead slot covers bouncing up and down. The frequency of the tapping was measured using a stopwatch and was measured at 4 cps. The force of the slot covers bouncing up and down could transmit enough energy to the tower to cause vibrations; however, since pressures were not directly measured in the slots, there were insufficient data to support this. The Little Rock District inspected the slot covers and determined that the tapping noise was coming from the slot cover for gate 1.

Service gates and staff gage vibrations

28. The acceleration data for the service gates and staff gage measurements are listed in Tables 6, 7, and 8. These data were not filtered because of the higher frequencies recorded by the accelerometers. Transducers GAV2, GAT2, GAP2, and GAV1 were damaged and did not produce a signal during tests 20-52. The vertical accelerometers (GV1 and GV2) located on the staff gages were installed after test 20. The measured gate accelerations were larger than those of the structures; however, the corresponding frequencies were higher than those frequencies that were considered to be causing the tower vibrations. The accelerations were largest at the higher gate openings. The accelerations measured on the staff gage for service gate 1 were higher than those measured for service gate 2. Typical gate acceleration time-history plots and FFT's are shown in Plate 6.

## Sluice Pressures

29. During all tests, sluice pressures were measured upstream (PUS) and downstream (PDS) of both service gates at the locations shown in Plate 1. The maximum, minimum, and mean pressures were determined from the digitized data time-histories along with the maximum instantaneous peak-to-peak pressure fluctuation for each test, and the range of frequency was obtained from the FFT plots. The pressure transducer downstream of service gate 2 (PDS2) was damaged during operation of the low-flow valve (test series B) and did not produce a signal. These pressures are listed in Tables 9 and 10. The sluice pressures measured upstream of the service gates indicated a high concentration of energy at lower frequencies ranging between 0.5 to 8.0 cps. These lower frequencies correlate with the 4-cps frequency exhibited by the intake tower and the wet well. The predominate frequencies downstream of the service gates ranged from 0.5 to 1.0 cps. The time-history and FFT plots are shown in Plates 7 and 8. The peak-to-peak pressure fluctuations upstream of the service gates were considerably greater than the peak-to-peak pressure fluctuations downstream. The upstream pressure fluctuations ranged from 0.76 to 2.3 ft for service gate 1 and from 0.28 to 4.3 ft for service gate 2, and the pressure fluctuations downstream ranged from 0.15 to 0.94 ft for service gate 1 and 0.12 to 0.56 ft for service gate 2. The highest pressure fluctuations measured were during tests in which service gate 1 was at an opening of 4.8 ft or greater.

30. Pressure fluctuations are listed nondimensionally in Table 11 in terms of the velocity head of the flow in the conduit. The data show that the pressure fluctuations upstream of service gate 1 are approximately expressed by

$$\frac{Pmax - Pmin}{\gamma} = 0.322 \frac{V^2}{2g} \qquad (2)$$

where

$\gamma$ = specific weight of fluid, lbs/ft$^3$

$\frac{V^2}{2g}$ = velocity head, ft

and for service gate 2

$$\frac{Pmax-Pmin}{\gamma} = .556 \frac{V^2}{2g} \tag{3}$$

Normal pressure fluctuations in turbulent flow are considered to be approximately 0.035 times the velocity head for Reynolds number greater than $5 \times 10^5$. This information was based on experimental data and isotropic turbulent flow models (Neilson 1971). Accordingly, the pressure fluctuations experienced at Gillham Dam are about 5 times the pressure fluctuations considered normal for turbulent flow. Plate 9 shows the maximum upstream instantaneous peak-to-peak pressure fluctuations in relation to normal pressure fluctuations for turbulent flow. These higher pressure fluctuations and the low range of frequencies seem to be the driving mechanism of the intake tower and wet well vibrations and could be the cause of the slot covers bouncing up and down.

31. Long blunt objects, such as trashracks, placed crosswise to a fluid flow can sometimes cause the shedding of eddies or vortices to occur. These vortices shed regularly and alternately from opposite sides of the object (Vennard and Street 1975). When the shedding frequency of the vortices approaches the natural frequency of the structure, large amplitude vibrations to the structure can be produced. The Strouhal number , s , which is a function of the object's geometry and Reynolds number for low Mach number flows, is the proportionality constant between the predominate frequency of vortex shedding and the free stream velocity divided by the maximum width of the object (Blevins 1977).

$$fs = \frac{Sv}{D} \tag{4}$$

where

fs = predominate frequency of vortex shedding, cps

v = free stream velocity, fps

D = maximum width of object normal to the free stream, ft

For Reynolds numbers between 60 and 5,000, the Strouhal number is approximately 0.21 (Vennard and Street 1975). Using an average conduit velocity and the maximum width of the trashracks, the predominate frequency of the vortex shedding was determined to be approximately fs = 4.2 cps. This frequency correlates with the frequencies exhibited by the intake tower and wet well and

is within the low frequency range of the upstream pressure fluctuations. This is a gross calculation of the shedding frequency, and further testing is needed to accurately determine the frequency of vortex shedding from the trashracks.

32. An attempt was made to determine if there was a relationship between the frequency of pressure fluctuations upstream of the service gates and the intake tower and wet well vibration frequencies. Plates 10-13 present the power spectral density, coherence, and cross-spectral density plots for test 31. The cross-spectral density function for two sets of random data describes the general dependance of the value of one set of data on the other (Bendat and Piersol 1958). The degree of dependance is expressed in the frequency domain. If there is a high level of dependance between two signals at a particular frequency, it will plot as a relatively discrete spike on the amplitude-frequency graph. It is evident from the plots that a relationship between the upstream pressure fluctuations (PUS1 and PUS2) and the intake tower accelerations (TAT and TAP) does exist at a 4-cps frequency. A prominent peak of the cross-spectral density plot at 4 cps coincides with the 4-cps frequency of the intake tower accelerations on the power spectral density plots. This relationship is more prominent for service gate 1. This indicates that the upstream pressure fluctuations are the driving force of the intake tower and wet well vibrations.

## Structural Dynamic Properties and Response of the Tower

33. The vibration data for the intake tower and wet well were examined more closely for response relating directly to the structural dynamic properties, specifically the natural frequencies, damping, and operating deflection shapes relating to natural mode shapes occurring at natural frequencies of the structure. The spectral density plots, as shown in Plates 10-13, show that the intake tower and wet well were excited or caused to vibrate at several of its natural frequencies. A simple calculation of the fundamental bending frequency of a cantilever beam, an ideal model of the tower, reveals that a natural frequency occurs near 2.9 cps. This frequency would be the first natural frequency in any direction assuming the structure is perfectly symmetric. However, because the structure is not perfectly symmetric, there exists a number of uncoupled and coupled modes that include bending and

torsional displacements of the intake tower and wet well. The data show the most significant natural frequencies corresponding to the bending and torsional vibrations occur between 0 and 20 cps.

34. The natural frequencies of a linear-elastic, idealized cantilever beam with uniform geometry throughout the height is given by Harris and Crede (1976) as:

$$\omega_n = A_n^*(EI/ul^4)^1/2 \tag{5}$$

and

$$f_n = 2\pi\omega_n \tag{6}$$

where

$\omega_n$ = the nth natural frequency, rad/sec

$f_n$ = the nth natural frequency, cps

$A_n$ = 3.52 for the fundamental bending mode (n = 1) and 22.4 for the second order bending mode (n = 2)

E = modulus of elasticity, psi

I = area moment of inertia of the uniform cross section, $in.^4$

u = mass per unit length, $lbs\text{-}sec^2/in.^2$

l = uniform length, in.

Using the above equations, the fundamental bending mode and the second order bending mode for the intake tower were determined to be $f_1$ = 3.9 cps and $f_2$ = 24.8 cps, respectively. This does not include the added water mass surrounding the tower. To account for the surrounding water mass, the fundamental bending mode and the second order bending mode were computed as $f_1$ = 2.9 cps and $f_2$ = 18.4 cps. To allow for flexibility of the foundation, the values of $f_1$ and $f_2$ would decrease further. The first natural frequencies for torsional and longitudinal modes of vibration of a cantilever are approximately 14 cps and 21 cps, respectively. This does not account for any added water mass.

35. These calculations are to show that the frequency responses observed in the data cover the ranges of the calculated natural frequencies. Furthermore, the spectral density characteristics of the pressure measurements show that energy has frequency content in the range of the observed and calculated bending and torsional responses of the intake tower. It is very likely that there exists coupled modes of vibration that correspond to peaks

in the autospectral and cross-spectral density plots. The existence of a 4-cps response is not unique; there do exist other responses of sufficient amplitude to warrant inspection of the correlation with the pressure and other acceleration measurements.

## Air Discharge

36. Pitot tube differential pressures were measured at the locations shown in Plates 1 and 2 for determining the air discharge in the vents supplying air to the sluices (AV1A, AV1B, AV1C, AV1D, and AV2) and to determine if any correlation exists between air fluctuations and sluice pressure fluctuations. All differential pressures were used to compute airflow into the sluices (upstream direction).

37. Velocity at a point Vp is proportional to the recorded differential pressure when measured by a pitot tube (Rouse 1962). This relation is given by the equation

$$Vp = K\sqrt{\Delta p} \tag{7}$$

where

K = constant of proportionality

$\Delta p$ = differential pressure between points A and B shown in Figure 8.

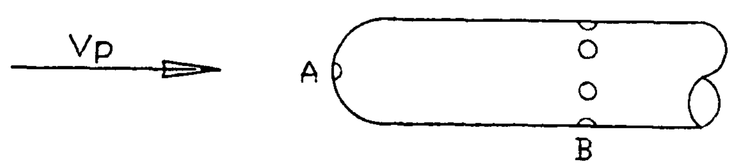


Figure 8. Pitot tube tip

38. The pitot tubes used in the Gillham Dam tests were calibrated by the National Space Technology Laboratories at Bay St. Louis, MS (Hart 1981). The calibrated value of K was determined to be 351.90. The Mach number for all point velocities measured was less than 0.30; therefore, the compressibility of air was not considered in the data analysis (Vennard and Street 1975).

39. The pitot tube support strut was located approximately 97.5 ft downstream from the vent exit. This corresponds to strut location of 48.75 equivalent diameters (De = 2.0 ft). The single pitot tube located in

air vent 2 was located approximately 94.5 ft downstream from the vent exit and corresponds to 47.25 equivalent diameters.

40. In air vent 1, the velocity distribution was assumed to be essentially uniform from wall to wall. This assumption is considered adequate due to the high Reynolds number computed for each test indicating turbulent flow and the fact that the measured data were essentially equal. Therefore, the velocity for air vent 1 was assumed to be the average of the four measurements (AV1A, AV1B, AV1C, and AV1D) while the velocities for air vent 2 was assumed to be the measured values of the single pitot tube, AV2. The standard deviation, on the average, was 2.7 percent of the mean implying that the assumption of uniform velocity distribution at the strut is reasonable. The velocities were multiplied by the cross-sectional area of the respective air vents to determine the discharge. Measured point velocities are given in Table 12 with the corresponding discharges presented in Table 13.

41. Kalinske and Robertson (1943) found the ratio of air demand to water discharge to be a function of the Froude number minus one. The Corps of Engineers combined this information with field measurements and derived a suggested design curve. The Gillham air vent discharges have been plotted on the Hydraulic Design Criteria (HDC) chart reproduced in Plate 14. The Froude number ($\mathcal{F}$) for the data was computed by

$$\mathcal{F} = \frac{V}{\sqrt{gy}} \tag{8}$$

where

V = water velocity at the vena contracta, fps

g = gravitational acceleration, ft/sec$^2$

y = water depth at the vena contracta, ft

According to HDC, the plotted discharges indicate that the air vent system at Gillham Dam seems to be providing sufficient air into the conduits.

42. Typical time-history and the corresponding FFT plots are shown in Plate 15. A gusting frequency of 0.5 cps was measured in all tests. This correlates with the frequencies measured by the downstream pressure transducers and indicates that the pressures downstream are cushioned by the airflow from the air vents. During operation of the low-flow valve, the air supply to gate 2 was immediately shut off and the differential pressure transducer in air vent 2 did not produce a signal. This is the result of the

low-flow pipe emptying into the conduit through the air vent. Air vent 2 acts as a piezometer during operation of the low-flow valve and a water column in air vent 2 rose above the placement of the transducer at el 487.0.

## PART IV: CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

43. The following conclusions and determinations result from field observations and analysis of the reduced Gillham Dam prototype data.

44. Conclusions relative to vibrations are as follows:

*a*. During tests in which motion occurred, a predominate frequency recorded for both the intake tower and the wet well was 4 cps and was predominate in the transverse and parallel direction to flow.

*b*. The frequencies were generally higher for the wet well.

*c*. Accelerations were highest during tests in which gate 1 was at an opening of 4.8 ft or higher. Vibration of the tower was most severe during tests in which gate 1 was at an opening of 5.15 ft (test 31).

*d*. Displacements and accelerations measured for the intake tower and wet well are considered troublesome and severe to persons.

*e*. The bouncing up and down of the bulkhead slot cover was determined to be the 4-cps tapping noise heard off the upstream side of the intake tower. This correlates with the structure's 4-cps predominate frequency. The force of the slot covers could transmit enough energy to cause the tower to vibrate; however, there are insufficient data to support this.

*f*. The service gate accelerations were greater during tests with the higher gate openings, and the staff gage vertical accelerations for service gate 1 were greater than for service gate 2. Service gate frequencies do not seem to correlate with pressure fluctuations and tower vibrations.

45. Conclusions relative to sluice pressures are as follows:

*a*. Significant correlation exists between the upstream pressure fluctuations and the intake tower and wet well vibrations.

*b*. The pressure fluctuations are approximately 5 times the pressure fluctuations considered normal for turbulent flow and therefore seems to be the driving force of the intake tower and wet well vibrations.

*c*. The downstream pressure fluctuations are not a cause of the structure's vibrations.

*d*. The frequency produced by vortex shedding from the trashracks is approximately 4.2 cps which correlates with the intake tower and wet well frequency. Further testing is needed to accurately determine the shedding frequency.

*e*. The cross-spectral density plots indicate a relationship between the upstream pressure fluctuations and the intake tower, and wet well exists at a 4-cps frequency and that the

pressure fluctuations are the driving force of the intake tower and wet well vibrations.

46. Conclusions relative to air discharge are as follows:

a. The air vent system provides sufficient air into the conduits and is not a problem.

b. During operation of the low-flow valve, the air supply to gate 2 is immediately shutoff as a result of the low flow emptying into the conduit through the air vent.

## Recommendations

47. Since these tests were performed, the Little Rock District installed a vent system that vents the bulkhead slot covers to the atmosphere (Figure 9). This vent system consists of a single 10-in.-diam PVC pipe that

Figure 9. Bulkhead slot vent system

extends from near the top of the intake tower at el 583.0, down the side of the tower to approximately el 503.0, where it transitions into two 6-in.-diam galvanized steel pipes via a galvanized steel Tee. Each leg of the Tee extends to a slot cover where the pipe makes a 90-degree turn down into the slot cover. The Tee connection is constructed such that it can be

disconnected from the 10-in.-diam pipe and slot covers when access to the slots is necessary. The top of the pipe is turned down and covered with screen to prevent possible blockage of the pipe. This vent system is not sized for any particular flow. It is not intended to provide an air supply to the upstream side of the gates, but to provide relief to any pressure fluctuations that develop upstream of the bulkhead slots. These pressure fluctuations have damaged the slot covers in the past and are believed to be the forcing function that is causing the tower vibrations to occur. Since the vent system has been installed (fall, 1991), there have been three events which produced conditions (pool elevation and discharge) that have caused vibrations in the past. During each event, there was no evidence of vibration in the tower. The tower is closely monitored during these conditions so that if vibrations do occur, corrective measures can be taken.

48. If additional vibrations are experienced with the vent system in place, it is recommended that additional tests be conducted with instruments installed in and around the bulkhead slot covers and, if possible, the trash-racks. This will help to narrow the region in which the pressure fluctuations are most severe and to determine if the slot covers are the source of the vibrations. It is recommended that the slot covers be removed and a screen be installed. It is also recommended that a structural analysis be conducted on the tower to determine how much motion the tower can withstand.

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Table 1

Gillham Dam Prototype Test

Test Schedule

| Series | Test | Gate #1 (ft) | Gate #2 (ft) | Air-vent | Low-flow | Comments |
|---|---|---|---|---|---|---|
| A | 1 | Closed | 3.0 | Open | Closed | Normal vibrations. |
| A | 2 | Closed | 4.0 | Open | Closed | |
| A | 3 | Closed | 4.6 | Open | Closed | Tapping noise occurring off wet well. Vibrations slightly increased. Vibrations at high frequencies. |
| A | 4 | Closed | 4.8 | Open | Closed | |
| A | 5 | Closed | 5.0 | Open | Closed | |
| A | 6 | Closed | 5.2 | Open | Closed | |
| A | 7 | Closed | 6.0 | Open | Closed | Tapping noise stopped. |
| A | 8 | 1.0 | 5.0 | Open | Closed | Data collected while lowering gate #2, maintaining 1680 cfs discharge. |
| A | 9 | 3.0 | 3.2 | Open | Closed | Gate setting for overnight discharge. Next morning: Intake tower moving in both parallel and tangential directions. Rhythmic banging, sounds like train (150/min). +/- 12g pops on GAP2 - increasing in intensity. All vibrations at high frequencies. |
| D | 10 | 3.0 | Closed | Open | Closed | Tapping/train noise started. |
| D | 11 | 4.0 | Closed | Open | Closed | Tapping/train noise increased, 180/min. |
| D | 12,13 | 4.6 | Closed | Open | Closed | |
| D | 14 | 4.8 | Closed | Open | Closed | Tapping/train noise increased, 200/min. Slight increase in tower movement. |
| D | 15 | 5.0 | Closed | Open | Closed | Tapping/train intensity increased, 220/min. Increase in tower movement. |
| D | 16 | 5.2 | Closed | Open | Closed | |

(Continued)

Table 1 (Continued)

| Series | Test | Gate #1 (ft) | Gate #2 (ft) | Air-vent | Low-flow | Comments |
|---|---|---|---|---|---|---|
| D | 17 | 6.0 | Closed | Open | Closed | While opening gate 1, the noise intensity increased until gate setting passed 5.4, then stopped. Tapping increased to 300/min. Tower motion did same. |
| D | 18 | 5.7 | Closed | Open | Closed | Moved gate opening from 6.0 to 5.4 to 5.7 ft. Structure moved significantly just prior to gate stopping. Motion decreased as very high frequencies and high 'g'-levels began on gate. Medium range whistle noise began inside tower. |
| D | 19 | 5.6 | Closed | Open | Closed | Whistle still noticed. Structure is vibrating - slight increase. |
| F | 20 | 3.0 | 3.0 | Open | Closed | Normal vibrations. **Refer to test 9A** Lost gages GAV2 and GAP2. |
| F | 21,22 | 4.0 | 4.0 | Open | Closed | Tapping/train noise started, 180/min. |
| F | 23 | 4.6 | 4.6 | Open | Closed | Tapping/train noise increased, 210/min. Slight increase in tower vibrations. |
| F | 24 | 4.8 | 4.8 | Open | Closed | |
| F | 25 | 5.0 | 5.0 | Open | Closed | Tower motion increased immediately. Lost gage GAT2 |
| F | 26,27, 28 | 5.2 | 5.2 | Open | Closed | Tapping/train noise increased with time, from 235/min to 270/min. Tower movement increases with time. Low frequency vibrations (3-4 Hz) increasing. |
| F | 29,30 | 5.1 | 5.1 | Open | Closed | |
| F | 31 | 5.15 | 5.15 | Open | Closed | Gage TAP was not working properly prior to this test. Prominent motion in tower. |
| F | 32 | 5.4 | 5.4 | Open | Closed | Normal vibrations in tower. Tapping intensity increased to >400/min. |
| F | 33,34 | 5.0 | 5.0 | Open | Closed | |

(Continued)

Table 1 (Continued)

| Series | Test | Gate #1 (ft) | Gate #2 (ft) | Air-vent | Low-flow | Comments |
|---|---|---|---|---|---|---|
| F | 35 | 4.8 | 4.8 | Open | Closed | |
| I | 36 | 5.6 | 3.0 | Open | Closed | Tapping/train started, >300/min. While changing gate settings, felt vibration in tower around 5.1 ft. Normal vibrations at this setting. |
| I | 37,38 | 5.1 | 3.0 | Open | Closed | Tapping/train intensity about 240/min. Tower started vibrating immediately and is increasing with time. |
| I | 39 | 5.2 | 4.0 | Open | Closed | Tower vibration decreased slightly. |
| I | 40 | 5.2 | 4.6 | Open | Closed | Tower vibration decreasing slightly. |
| I | 41 | 5.2 | 4.8 | Open | Closed | Tower vibration starting to increase. |
| I | 42 | 5.2 | 5.0 | Open | Closed | Tower vibration increasing/decreasing in a cyclic pattern. |
| I | 43,44 | 5.2 | 5.2 | Open | Closed | |
| J | 45 | 3.0 | 5.2 | Open | Closed | Normal vibrations. |
| J | 46 | 4.0 | 5.2 | Open | Closed | Tapping/train intensity 190/min. |
| J | 47 | 5.0 | 5.2 | Open | Closed | Tapping/train increased to 240/min. Tower vibration increased immediately, tends to be cyclic. |
| B | 48 | 5.0 | 5.0 | Open | 45 | No change from test 3J. No air flow in vent #2. Lost gage PDS2. Water coming through air vent #2. |
| B | 49 | 5.0 | 5.0 | Open | 90 | |
| B | 50 | 4.0 | 4.0 | Open | 45 | Decrease in tapping/train noise - 160/min. Significant decrease in tower vibrations. Cavitation occurring in conduit #2. No air flow in #2. |
| B | 51 | 4.0 | 4.0 | Open | 90 | |
| B | 52 | 3.0 | 3.0 | Open | 45 | Vibration/noise continuing to decrease. |
| B | 53 | 3.0 | 3.0 | Open | 90 | Data recorded on mag tape. |

(Continued)

Table 1 (Concluded)

| Series | Test | Gate #1 (ft) | Gate #2 (ft) | Air-vent | Low-flow | Comments |
|---|---|---|---|---|---|---|
| B | 54 | 2.0 | 2.0 | Open | 45 | |
| B | 55 | 2.0 | 2.0 | Open | 90 | |
| B | 56 | 0.9 | 0.9 | Open | 45 | |
| B | 57 | 0.9 | 0.9 | Open | 90 | |

(Sheet 4 of 4)

Table 2

Summary of Instrumentation

| Code | Transducer Description Type | Range | Transducer Location | Elev. | Cable Length (ft) | Meas. | Computed Quantity |
|---|---|---|---|---|---|---|---|
| PUS1<br>PUS2 | Absolute Pressure Cell | 100 psia | Upstream of service gate 1 and 2 | 447.0 | 230 | Press. | Press. fluctuations |
| PDS1<br>PDS2 | Absolute Pressure Cell | 50 psia | Downstream of service gate 1 and 2 | 447.0 | 230 | Press. | Press. fluctuations |
| PWS | Absolute Pressure Cell | 50 psia | 10 ft below water surface | 534.0 | 50 | Press. | Water-surface elev. |
| AV1A<br>AV1B<br>AV1C<br>AV1D | Differential Pressure Cell | 0.5 psid | Left air vent | 484.0 | 200 | Diff Press. | Air-vent velocity |
| AV2 | Differential Pressure Cell | 0.5 psid | Right air vent | 487.0 | 200 | Diff Press. | Air-vent velocity |
| TAV<br>TAT<br>TAP | Accelerometer | 1 g-25g | Roof of intake tower | 586.0 | 100 | Accel. | Vert. displ./freq.<br>Trans. displ./freq.<br>Parall.displ./freq. |
| WAV<br>WAT<br>WAP | Accelerometer | 1 g-25g | Roof of wet well | 529.8 | 250 | Accel. | Vert. displ./freq.<br>Trans. displ./freq.<br>Parall.displ./Freq. |
| GAV1<br>GAT1<br>GAP1 | Accelerometer | 2.5g | Service gate 1 | 438.5 | 200 | Accel. | Vert. displ./freq.<br>Trans. displ./freq.<br>Parall.displ./freq. |
| GAV2<br>GAT2 | Accelerometer | 2.5g | Service gate 2 | 438.5 | 200 | Accel. | Vert. displ./freq.<br>Trans. displ./freq. |

(Continued)

Table 2 (Concluded)

| Code | Transducer Description Type | Range | Transducer Location | Elev. | Cable Length (ft) | Meas. | Computed Quantity |
|---|---|---|---|---|---|---|---|
| GAP2 | | | | | | | Parall.displ./freq. |
| GAV1<br>GAV2 | Accelerometer | 2.5g | Staff gage of each service gate | 465.0 | 200 | Accel. | Vert. displ./freq. |

Table 3

Evaluated Test Conditions

| Test No. | Gate 1 Opening ft | Gate 2 Opening ft | Low Flow Opening deg | Pool Elev ft | Water Discharge cfs | Conduit Velocity fps |
|---|---|---|---|---|---|---|
| 12 | 4.6 | 0 | closed | 544.58 | 1260 | 16.0 |
| 13 | 4.6 | 0 | closed | 544.58 | 1260 | 16.0 |
| 17 | 6.0 | 0 | closed | 544.53 | 1680 | 21.4 |
| 20 | 3.0 | 3.0 | closed | 544.50 | 1620 | 20.6 |
| 31 | 5.15 | 5.15 | closed | 543.39 | 2790 | 35.5 |
| 36 | 5.6 | 3.0 | closed | 542.25 | 2360 | 30.0 |
| 38 | 5.1 | 3.0 | closed | 542.22 | 2220 | 28.3 |
| 45 | 3.0 | 5.2 | closed | 541.94 | 2230 | 28.4 |
| 47 | 5.0 | 5.2 | closed | 541.90 | 2780 | 35.4 |
| 48 | 5.0 | 5.0 | 45 | 541.87 | 2775 | 35.5 |
| 49 | 5.0 | 5.0 | 90 | 541.85 | 2900 | 36.9 |
| 52 | 3.0 | 3.0 | 45 | 541.80 | 1675 | 21.3 |

Table 4

Intake Tower Vibrations

| Test No. | Transducer Location | Max g | Min g | P-P g | Freq Hz | RMS g | Disp in. |
|---|---|---|---|---|---|---|---|
| 12 | Vertical | 0.036 | -0.042 | 0.064 | 4.0 | 0.0074 | 0.0391 |
| | Transverse | 0.022 | -0.027 | 0.042 | 3.5 | 0.0056 | 0.0032 |
| | Parallel | -0.013 | -0.049 | 0.025 | 0.5 | 0.0037 | 0.9749 |
| 13 | Vertical | 0.038 | -0.040 | 0.070 | 4.5 | 0.0068 | 0.0338 |
| | Transverse | 0.023 | -0.026 | 0.043 | 3.5 | 0.0056 | 0.0348 |
| | Parallel | -0.136 | -0.169 | 0.024 | 0.5 | 0.0037 | 0.9514 |
| 17 | Vertical | 0.031 | -0.037 | 0.062 | 5.0 | 0.0081 | 0.0243 |
| | Transverse | 0.024 | -0.033 | 0.042 | 5.0 | 0.0056 | 0.0163 |
| | Parallel | 0.022 | -0.012 | 0.029 | 4.0 | 0.0037 | 0.0175 |
| 20 | Vertical | 0.026 | -0.030 | 0.046 | 4.0 | 0.0062 | 0.0281 |
| | Transverse | 0.015 | -0.026 | 0.034 | 4.5 | 0.0050 | 0.0162 |
| | Parallel | 0.030 | -0.004 | 0.025 | 8.0 | 0.0037 | 0.0390 |
| 31 | Vertical | 0.038 | -0.047 | 0.072 | 5.5 | 0.0081 | 0.0233 |
| | Transverse | 0.025 | -0.035 | 0.054 | 4.0 | 0.0062 | 0.0331 |
| | Parallel | 0.030 | -0.037 | 0.053 | 4.0 | 0.0081 | 0.0324 |
| 36 | Vertical | 0.061 | -0.030 | 0.074 | 6.5 | 0.0062 | 0.0171 |
| | Transverse | 0.065 | -0.057 | 0.080 | 5.5 | 0.0050 | 0.0257 |
| | Parallel | 0.032 | -0.032 | 0.047 | 5.5 | 0.0050 | 0.0151 |
| 38 | Vertical | 0.041 | -0.042 | 0.067 | 8.0 | 0.0074 | 0.0102 |
| | Transverse | 0.025 | -0.032 | 0.054 | 4.0 | 0.0056 | 0.0278 |
| | Parallel | 0.034 | -0.034 | 0.054 | 4.0 | 0.0068 | 0.0331 |
| 45 | Vertical | 0.030 | -0.020 | 0.043 | 4.0 | 0.0050 | 0.0266 |
| | Transverse | 0.019 | -0.021 | 0.033 | 5.0 | 0.0044 | 0.0129 |
| | Parallel | 0.019 | -0.021 | 0.030 | 5.0 | 0.0044 | 0.0119 |
| 47 | Vertical | 0.040 | -0.032 | 0.066 | 2.0 | 0.0068 | 0.0162 |
| | Transverse | 0.025 | -0.030 | 0.047 | 4.0 | 0.0056 | 0.0289 |
| | Parallel | 0.029 | -0.030 | 0.047 | 4.0 | 0.0068 | 0.0289 |
| 48 | Vertical | 0.048 | -0.034 | 0.067 | 2.5 | 0.0074 | 0.1049 |
| | Transverse | 0.030 | -0.039 | 0.047 | 4.0 | 0.0056 | 0.0289 |
| | Parallel | 0.032 | -0.035 | 0.053 | 4.0 | 0.0068 | 0.0327 |
| 49 | Vertical | 0.045 | -0.038 | 0.072 | 2.0 | 0.0081 | 0.1762 |
| | Transverse | 0.027 | -0.038 | 0.055 | 4.0 | 0.0068 | 0.0334 |
| | Parallel | 0.029 | -0.034 | 0.050 | 4.0 | 0.0068 | 0.0308 |
| 52 | Vertical | 0.032 | -0.022 | 0.048 | 1.5 | 0.0056 | 0.2081 |
| | Transverse | 0.019 | -0.024 | 0.034 | 5.0 | 0.0050 | 0.0131 |
| | Parallel | 0.016 | -0.025 | 0.029 | 2.5 | 0.0044 | 0.0457 |

Table 5

Wet Well Vibrations

| Test No. | Transducer Location | Max g | Min g | P-P g | Freq Hz | RMS g | Disp in. |
|---|---|---|---|---|---|---|---|
| 12 | Vertical | 0.025 | -0.017 | 0.035 | 0.5 | 0.0043 | 1.3700 |
| | Transverse | 0.020 | -0.023 | 0.037 | 5.5 | 0.0055 | 0.0120 |
| | Parallel | 0.024 | -0.019 | 0.033 | 5.0 | 0.0044 | 0.0129 |
| 13 | Vertical | 0.028 | -0.015 | 0.035 | 0.5 | 0.0043 | 1.3550 |
| | Transverse | 0.023 | -0.023 | 0.039 | 2.5 | 0.0055 | 0.0608 |
| | Parallel | 0.023 | -0.020 | 0.037 | 3.5 | 0.0044 | 0.0295 |
| 17 | Vertical | 0.029 | -0.018 | 0.044 | 0.5 | 0.0056 | 1.7460 |
| | Transverse | 0.023 | -0.027 | 0.049 | 5.0 | 0.0055 | 0.0193 |
| | Parallel | 0.018 | -0.028 | 0.036 | 5.0 | 0.0056 | 0.0139 |
| 20 | Vertical | 0.020 | -0.021 | 0.028 | 0.5 | 0.0043 | 1.0880 |
| | Transverse | 0.013 | -0.023 | 0.033 | 4.5 | 0.0043 | 0.0158 |
| | Parallel | 0.016 | -0.025 | 0.032 | 6.0 | 0.0044 | 0.0088 |
| 31 | Vertical | 0.033 | -0.021 | 0.038 | 0.5 | 0.0056 | 1.4990 |
| | Transverse | 0.032 | -0.047 | 0.070 | 4.0 | 0.0105 | 0.0426 |
| | Parallel | 0.018 | -0.031 | 0.036 | 4.0 | 0.0050 | 0.0218 |
| 36 | Vertical | 0.057 | -0.002 | 0.039 | 0.5 | 0.0049 | 1.5460 |
| | Transverse | 0.049 | -0.052 | 0.068 | 3.0 | 0.0099 | 0.0737 |
| | Parallel | 0.038 | -0.024 | 0.047 | 10.5 | 0.0044 | 0.0042 |
| 38 | Vertical | 0.045 | -0.004 | 0.035 | 0.5 | 0.0056 | 1.3780 |
| | Transverse | 0.035 | -0.051 | 0.067 | 4.0 | 0.0105 | 0.0407 |
| | Parallel | 0.021 | -0.029 | 0.032 | 4.0 | 0.0050 | 0.0195 |
| 45 | Vertical | 0.028 | -0.011 | 0.030 | 0.5 | 0.0037 | 1.1590 |
| | Transverse | 0.031 | -0.045 | 0.065 | 4.5 | 0.0092 | 0.0316 |
| | Parallel | 0.018 | -0.023 | 0.029 | 5.0 | 0.0038 | 0.0115 |
| 47 | Vertical | 0.041 | -0.007 | 0.033 | 0.5 | 0.0056 | 1.3080 |
| | Transverse | 0.035 | -0.045 | 0.073 | 2.5 | 0.0105 | 0.1149 |
| | Parallel | 0.016 | -0.027 | 0.031 | 4.0 | 0.0044 | 0.0187 |
| 48 | Vertical | 0.028 | -0.029 | 0.046 | 3.0 | 0.0062 | 0.0503 |
| | Transverse | 0.040 | -0.056 | 0.073 | 9.0 | 0.0123 | 0.0878 |
| | Parallel | 0.023 | -0.030 | 0.038 | 9.0 | 0.0056 | 0.0046 |
| 49 | Vertical | 0.088 | -0.067 | 0.115 | 8.5 | 0.0117 | 0.0156 |
| | Transverse | 0.106 | -0.163 | 0.261 | 10.0 | 0.0197 | 0.0255 |
| | Parallel | 0.039 | -0.058 | 0.087 | 10.0 | 0.0088 | 0.0085 |
| 52 | Vertical | 0.023 | -0.028 | 0.043 | 5.0 | 0.0062 | 0.0167 |
| | Transverse | 0.037 | -0.055 | 0.071 | 9.0 | 0.0117 | 0.0086 |
| | Parallel | 0.018 | -0.031 | 0.036 | 9.0 | 0.0050 | 0.0043 |

Table 6

Service Gate Vibrations

Gate 1

| Test No. | Transducer Location | Max g | Min g | P-P g | Low Freq Hz | High Freq Hz | RMS g | Low Disp in. E-03 | High Disp in. E-03 |
|---|---|---|---|---|---|---|---|---|---|
| 12 | Vertical | 0.194 | -0.219 | 0.357 | 38.5 | 228.0 | 0.0376 | 2.358 | 0.0672 |
| | Transverse | 0.105 | -0.100 | 0.210 | 38.5 | 212.5 | 0.0185 | 1.385 | 0.0455 |
| | Parallel | 0.599 | -0.698 | 1.185 | 48.5 | 218.0 | 0.1111 | 4.931 | 0.2240 |
| 13 | Vertical | 0.194 | -0.213 | 0.301 | 38.5 | 231.5 | 0.0376 | 1.985 | 0.0549 |
| | Transverse | 0.191 | -0.154 | 0.204 | 38.5 | 205.0 | 0.0185 | 1.345 | 0.0474 |
| | Parallel | 0.821 | -0.901 | 1.284 | 48.5 | 215.5 | 0.1049 | 5.343 | 0.2706 |
| 17 | Vertical | 0.282 | -0.219 | 0.470 | 38.5 | 228.0 | 0.0501 | 3.103 | 0.0885 |
| | Transverse | 0.160 | -0.173 | 0.247 | 38.5 | 216.5 | 0.0247 | 1.630 | 0.0515 |
| | Parallel | 0.784 | -0.778 | 1.500 | 50.0 | 227.5 | 0.1235 | 5.872 | 0.2837 |
| 20 | Vertical | 0.251 | -0.282 | 0.019 | 38.5 | ** | 0.0439 | ** | ** |
| | Transverse | 0.191 | -0.160 | 0.049 | 38.5 | ** | 0.0247 | ** | ** |
| | Parallel | 0.975 | -0.975 | 0.055 | 38.5 | ** | 0.1667 | ** | ** |
| 31 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.136 | -0.179 | 0.265 | 53.0 | 198.0 | 0.0247 | 0.0923 | 0.0661 |
| | Parallel | 0.667 | -0.642 | 1.185 | 95.0 | 193.5 | 0.1111 | 1.2850 | 0.3098 |
| 36 | Vertical | — | — | — | — | — | — | 1.3630 | — |
| | Transverse | 0.506 | -0.611 | 1.006 | 85.0 | 242.5 | 0.0679 | 18.7600 | 0.1674 |
| | Parallel | 0.741 | -0.728 | 1.296 | 26.0 | 236.0 | 0.1543 | — | 0.2277 |
| 38 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.136 | -0.284 | 0.321 | 38.5 | 200.0 | 0.0247 | 2.120 | 0.0785 |
| | Parallel | 0.611 | -0.772 | 1.278 | 104.5 | 232.5 | 0.1173 | 1.145 | 0.2314 |
| 45 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.228 | -0.228 | 0.265 | 18.5 | 251.0 | 0.0309 | 7.578 | 0.0412 |
| | Parallel | 0.709 | -1.000 | 1.679 | 83.5 | 222.5 | 0.1543 | 2.357 | 0.3319 |
| 47 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.259 | -0.426 | 0.413 | 38.5 | 207.5 | 0.0247 | 2.727 | 0.0939 |
| | Parallel | 0.728 | -0.772 | 1.352 | 99.5 | 234.0 | 0.1235 | 1.337 | 0.2417 |
| 48 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.346 | -0.278 | 0.370 | 38.5 | 210.0 | 0.0247 | 2.443 | 0.0821 |
| | Parallel | 0.698 | -0.796 | 1.426 | 98.0 | 237.0 | 0.1235 | 1.453 | 0.2485 |

(Continued)

** Data was lost for frequencies greater than 100 Hz.

— Lost gage GAV1 during Test 20.

Table 6 (Concluded)

| Test No. | Transducer Location | Max g | Min g | P–P g | Low Freq Hz | High Freq Hz | RMS g | Low Disp in. E–03 | High Disp in. E–03 |
|---|---|---|---|---|---|---|---|---|---|
| 49 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.167 | –0.210 | 0.302 | 38.5 | 212.0 | 0.0247 | 1.994 | 0.0658 |
| | Parallel | 0.679 | –0.889 | 1.407 | 100.5 | 233.5 | 0.1235 | 1.363 | 0.2526 |
| 52 | Vertical | — | — | — | — | — | — | — | — |
| | Transverse | 0.136 | –0.204 | 0.216 | 26.5 | 251.0 | 0.0247 | 3.010 | 0.0335 |
| | Parallel | 0.796 | –1.012 | 1.679 | 102.0 | 202.0 | 0.1420 | 1.579 | 0.4027 |

Table 7

Service Gate Vibrations

Gate 2

| Test No. | Transducer Location | Max g | Min g | P-P g | Low Freq Hz | High Freq Hz | RMS g | Low Disp in. E-03 | High Disp in. E-03 |
|---|---|---|---|---|---|---|---|---|---|
| 12 | Vertical | 0.025 | -0.038 | 0.050 | 38.5 | 251.0 | 0.0063 | 0.3315 | 0.0672 |
| | Transverse | 0.037 | -0.037 | 0.055 | 38.5 | 251.0 | 0.0062 | 0.3665 | 0.0455 |
| | Parallel | 0.025 | -0.031 | 0.044 | 38.5 | 251.0 | 0.0063 | 0.2905 | 0.2240 |
| 13 | Vertical | 0.025 | -0.038 | 0.044 | 38.5 | 251.0 | 0.0063 | 0.2905 | 0.0549 |
| | Transverse | 0.037 | -0.037 | 0.062 | 38.5 | 251.0 | 0.0062 | 0.4074 | 0.0474 |
| | Parallel | 0.031 | -0.031 | 0.044 | 38.5 | 251.0 | 0.0063 | 0.2905 | 0.2706 |
| 17 | Vertical | 0.025 | -0.038 | 0.050 | 38.5 | 251.0 | 0.0063 | 0.3302 | 0.0885 |
| | Transverse | 0.037 | -0.049 | 0.074 | 38.5 | 251.0 | 0.0062 | 0.4886 | 0.0515 |
| | Parallel | 0.025 | -0.031 | 0.044 | 38.5 | 251.0 | 0.0063 | 0.2905 | 0.2837 |

* Lost accelerometers on Gate 2 during Test 20.

Table 8

Service Gates Staff Gage Vibrations

Vertical Accelerometers Only

| Test No. | Transducer Location | Max g | Min g | P-P g | Low Freq Hz | High Freq Hz | RMS g | Low Disp in. E-03 | High Disp in. E-03 |
|---|---|---|---|---|---|---|---|---|---|
| 31 | Gate 1 | 3.518 | -3.103 | 5.226 | 57.5 | 217.0 | 0.3392 | 15.470 | 1.0860 |
| | Gate 2 | 1.006 | -1.006 | 1.938 | 54.5 | 229.0 | 0.2160 | 6.386 | 0.3617 |
| 36 | Gate 1 | 2.098 | -1.997 | 3.197 | 26.0 | 242.5 | 0.5151 | 46.290 | 0.5321 |
| | Gate 2 | 1.858 | -2.099 | 2.802 | 88.5 | 208.5 | 0.2346 | 3.501 | 0.6309 |
| 38 | Gate 1 | 0.879 | -0.861 | 1.489 | 57.5 | 224.0 | 0.1884 | 4.408 | 0.2904 |
| | Gate 2 | 2.117 | -2.025 | 3.000 | 88.0 | 208.0 | 0.5407 | 3.792 | 0.6787 |
| 45 | Gate 1 | 3.354 | -4.497 | 4.680 | 68.0 | 221.0 | 0.2952 | 9.906 | 0.9379 |
| | Gate 2 | 1.012 | -1.080 | 1.728 | 26.5 | 226.5 | 0.2346 | 24.080 | 0.3297 |
| 47 | Gate 1 | 3.838 | -3.769 | 7.041 | 70.5 | 222.0 | 0.5779 | 13.860 | 1.3980 |
| | Gate 2 | 1.284 | -1.154 | 2.111 | 26.5 | 196.5 | 0.2284 | 29.420 | 0.5351 |
| 48 | Gate 1 | 5.063 | -5.013 | 8.587 | 69.5 | 223.5 | 0.6156 | 17.400 | 1.6820 |
| | Gate 2 | 1.185 | -1.235 | 1.747 | 27.5 | 222.5 | 0.2346 | 22.610 | 0.3454 |
| 49 | Gate 1 | 3.580 | -4.139 | 7.720 | 68.0 | 223.5 | 0.6093 | 16.340 | 1.5130 |
| | Gate 2 | 2.198 | -1.889 | 3.200 | 27.5 | 219.0 | 0.3210 | 41.410 | 0.6530 |
| 52 | Gate 1 | 4.152 | -3.298 | 4.024 | 74.5 | 219.0 | 0.2701 | 7.096 | 0.8212 |
| | Gate 2 | 1.191 | -1.321 | 24.070 | 28.5 | 215.0 | 0.2654 | 29.000 | 0.5096 |

* Vertical accelerometers were mounted on staff gage prior to Test 31.

Table 9

Sluice Gate Pressures

Gage 1

| Test No. | Max ft | Mean ft | Min ft | RMS ft | P-P ft | Freq Hz |
|---|---|---|---|---|---|---|
| | PUS1 | | | | | |
| 12 | -3.313 | -4.243 | -5.716 | 0.3294 | 1.395 | 3.5 |
| 13 | -3.468 | -4.418 | -6.258 | 0.3294 | 1.240 | 6.5 |
| 17 | -6.452 | -7.460 | -10.056 | 0.4069 | 2.192 | 5.0 |
| 20 | -1.511 | -2.131 | -2.771 | 0.1550 | 0.930 | 6.0 |
| 31 | -5.580 | -6.646 | -8.758 | 0.3681 | 2.174 | 6.0 |
| 36 | -6.220 | -7.556 | -10.095 | 0.5231 | 2.286 | 8.0 |
| 38 | -5.231 | -6.142 | -7.692 | 0.3681 | 1.647 | 6.0 |
| 45 | -2.616 | -3.236 | -4.049 | 0.1938 | 1.260 | 4.0 |
| 47 | -5.115 | -6.375 | -8.893 | 0.4263 | 2.170 | 4.0 |
| 48 | -5.328 | -6.355 | -8.331 | 0.4069 | 1.683 | 4.0 |
| 49 | -5.173 | -6.297 | -7.983 | 0.3681 | 1.760 | 6.0 |
| 52 | -2.654 | -3.178 | -3.720 | 0.1550 | 0.756 | 4.0 |
| | PDS1 | | | | | |
| 12 | -1.916 | -2.042 | -7.127 | 0.0361 | 0.2350 | 3.0 |
| 13 | -1.157 | -1.265 | -1.392 | 0.0181 | 0.1460 | 3.5 |
| 17 | -1.211 | -1.305 | -1.446 | 0.0181 | 0.1450 | 6.5 |
| 20 | -1.482 | -1.645 | -1.880 | 0.0542 | 0.2350 | 5.0 |
| 31 | -1.283 | -1.428 | -1.609 | 0.0361 | 0.1800 | 3.0 |
| 36 | -2.078 | -2.585 | -3.018 | 0.1446 | 0.8670 | 2.5 |
| 38 | -2.078 | -2.566 | -3.109 | 0.1627 | 0.5240 | 3.0 |
| 45 | -2.133 | -2.675 | -3.127 | 0.1446 | 0.4700 | 2.0 |
| 47 | -1.952 | -2.097 | -2.313 | 0.0542 | 0.2350 | 2.5 |
| 48 | -2.494 | -2.874 | -3.416 | 0.1446 | 0.5420 | 2.5 |
| 49 | -2.404 | -2.639 | -3.000 | 0.0904 | 0.5420 | 2.0 |
| 52 | -2.422 | -2.928 | -13.100 | 0.1627 | 0.9400 | 6.0 |
| | -1.916 | -2.042 | -7.127 | 0.0361 | 0.2350 | 3.0 |

Table 10

Sluice Gate Pressures

Gage 2

| Test No. | PUS2 Max ft | Mean ft | Min ft | RMS ft | P-P ft | Freq Hz |
|---|---|---|---|---|---|---|
| 12 | -0.284 | -0.435 | -0.636 | 0.0502 | 0.2844 | 3.5 |
| 13 | -0.301 | -0.485 | -0.686 | 0.0502 | 0.2844 | 6.5 |
| 17 | -0.301 | -0.519 | -0.703 | 0.0669 | 0.3346 | 5.0 |
| 20 | -1.506 | -2.075 | -2.727 | 0.1673 | 0.9540 | 6.0 |
| 31 | -5.538 | -7.295 | -9.035 | 0.4685 | 2.5600 | 6.0 |
| 36 | -5.237 | -5.990 | -6.759 | 0.2175 | 1.3050 | 8.0 |
| 38 | -5.270 | -6.023 | -6.809 | 0.2175 | 1.3050 | 6.0 |
| 45 | -8.650 | -10.925 | -13.418 | 0.0856 | 4.0370 | 4.0 |
| 47 | -9.219 | -11.243 | -13.939 | 0.5187 | 4.3030 | 4.0 |
| 48 | -8.549 | -10.373 | -12.732 | 0.5019 | 2.7750 | 4.0 |
| 49 | -8.031 | -10.256 | -13.100 | 0.5856 | 4.0350 | 6.0 |
| 52 | -5.454 | -6.274 | -7.127 | 0.2342 | 1.3550 | 6.0 |
| | PDS2 | | | | | |
| 12 | -0.816 | -0.895 | -1.074 | 0.0199 | 0.1193 | 3.5 |
| 13 | -0.735 | -0.835 | -1.014 | 0.0199 | 0.1193 | 6.5 |
| 17 | -1.114 | -1.233 | -1.472 | 0.0398 | 0.2390 | 5.0 |
| 20 | -0.995 | -1.114 | -1.273 | 0.0398 | 0.1990 | 3.0 |
| 31 | -1.671 | -2.188 | -2.566 | 0.1392 | 0.5770 | 2.5 |
| 36 | 0.597 | 0.139 | -0.358 | 0.1591 | 0.4770 | 3.0 |
| 38 | 0.577 | 0.000 | -0.358 | 0.1392 | 0.3980 | 2.0 |
| 45 | 1.094 | 0.935 | 0.756 | 0.0398 | 0.1790 | 2.5 |
| 47 | 0.497 | 0.159 | -0.378 | 0.1392 | 0.5560 | 2.5 |
| 48 | ** | ** | ** | ** | ** | ** |
| 49 | ** | ** | ** | ** | ** | ** |
| 52 | ** | ** | ** | ** | ** | ** |

** Lost gage PDS2 during operation of low-flow valve.

Table 11

Nondimensional Pressure Fluctuations

| Test No. | $V^2/2g$ ft Gate 1 | $V^2/2g$ ft Gate 2 | $\frac{P_{max} - P_{min}/\gamma}{V^2/2g}$ PUS1 ft | PDS1 ft | PUS2 ft | PDS2 ft |
|---|---|---|---|---|---|---|
| 12 | 12.17 | 0 | 0.264 | 0.028 | * | * |
| 13 | 12.17 | 0 | 0.235 | 0.027 | * | * |
| 17 | 21.64 | 0 | 0.234 | 0.025 | * | * |
| 20 | 5.03 | 5.03 | 0.427 | 0.083 | 0.438 | 0.091 |
| 31 | 14.92 | 14.92 | 0.336 | 0.134 | 0.396 | 0.089 |
| 36 | 18.18 | 5.16 | 0.290 | 0.066 | 0.584 | 0.213 |
| 38 | 14.81 | 5.28 | 0.257 | 0.073 | 0.570 | 0.174 |
| 45 | 5.16 | 15.24 | 0.564 | 0.105 | 0.611 | 0.027 |
| 47 | 14.39 | 15.24 | 0.348 | 0.087 | 0.652 | 0.084 |
| 48 | 14.08 | 14.08 | 0.276 | 0.089 | 0.455 | ** |
| 49 | 14.08 | 14.08 | 0.288 | 0.154 | 0.661 | ** |
| 52 | 5.03 | 5.03 | 0.347 | 0.108 | 0.622 | ** |
| | | Avg | 0.322 | 0.082 | 0.556 | 0.113 |

* Gate 2 was closed during these tests.

** Lost gage PDS2 during operation of low flow valve.

Table 12

Air Vent Point Velocities

| Test No. | Item | AV1A fps | AV1B fps | AV1C fps | AV1D fps | Ave fps | $R_e$ x $10^6$ | AV2 fps | $R_e$ x $10^6$ |
|---|---|---|---|---|---|---|---|---|---|
| 12 | Max | 125.41 | 117.77 | 117.77 | 11.13 | 93.02 | 6.790 | 11.13 | 1.085 |
| | Mean | 90.40 | 93.10 | 84.01 | 11.13 | 69.66 | 6.796 | 11.13 | 1.085 |
| | Min | 33.38 | 61.95 | * | 11.13 | 32.83 | 3.203 | 11.13 | 1.085 |
| | Max | 124.40 | 116.72 | 118.81 | 115.11 | 118.76 | 11.590 | 111.28 | 10.850 |
| 13 | Mean | 89.72 | 91.76 | 84.75 | 81.01 | 86.81 | 8.469 | 91.76 | 8.952 |
| | Min | * | 52.19 | 0 | 0 | 15.83 | 1.544 | 65.83 | 6.4222 |
| | Max | 163.17 | 159.33 | 158.16 | 153.79 | 158.61 | 15.470 | 165.80 | 16.170 |
| 17 | Mean | 128.33 | 134.46 | 120.37 | 116.71 | 124.97 | 12.190 | 136.74 | 13.340 |
| | Min | 93.77 | 97.01 | 66.77 | 65.83 | 80.84 | 7.887 | 106.74 | 10.410 |
| | Max | 131.67 | 145.94 | 126.88 | 121.90 | 131.60 | 12.840 | 127.37 | 12.430 |
| 20 | Mean | 102.59 | 129.77 | 97.01 | 90.40 | 104.94 | 10.240 | 107.89 | 10.530 |
| | Min | 76.29 | 108.46 | 60.95 | 53.37 | 74.77 | 7.294 | 84.75 | 8.268 |
| | Max | 212.89 | 226.15 | 212.02 | 202.15 | 213.30 | 20.810 | 207.59 | 20.250 |
| 31 | Mean | 202.46 | 212.31 | 190.16 | 181.49 | 196.60 | 19.180 | 205.49 | 20.050 |
| | Min | 143.81 | 156.98 | 106.15 | 109.03 | 128.99 | 12.580 | 165.06 | 16.100 |
| | Max | 212.89 | 226.15 | 212.02 | 202.15 | 213.30 | 20.810 | 207.59 | 20.250 |
| 36 | Mean | 190.16 | 192.42 | 177.35 | 162.03 | 180.49 | 17.610 | 197.82 | 19.300 |
| | Min | 137.19 | 136.74 | 100.15 | 94.42 | 117.12 | 11.430 | 141.64 | 13.820 |
| | Max | 212.89 | 226.15 | 212.02 | 202.15 | 213.30 | 20.810 | 207.59 | 20.250 |
| 38 | Mean | 198.75 | 203.68 | 180.81 | 170.59 | 188.46 | 18.390 | 203.37 | 19.840 |
| | Min | 144.24 | 152.98 | 114.03 | 99.53 | 127.69 | 12.460 | 147.21 | 14.360 |
| | Max | 157.37 | 150.54 | 149.71 | 143.81 | 150.36 | 14.670 | 154.19 | 15.040 |
| 45 | Mean | 119.33 | 122.41 | 110.72 | 107.31 | 114.94 | 11.210 | 124.41 | 12.140 |
| | Min | 87.62 | 91.76 | 60.95 | 59.93 | 75.06 | 7.323 | 93.77 | 9.148 |
| 47 | Max | 212.89 | 226.15 | 212.02 | 202.15 | 190.55 | 18.590 | 207.59 | 20.250 |
| | Mean | 188.52 | 192.42 | 171.31 | 162.03 | 178.57 | 17.420 | 188.19 | 18.360 |
| | Min | 136.74 | 149.30 | 93.77 | 98.91 | 119.68 | 11.680 | 143.81 | 14.030 |
| 48 | Max | 208.78 | 208.48 | 209.39 | 196.24 | 205.72 | 20.070 | ** | ** |
| | Mean | 170.59 | 182.17 | 152.98 | 147.21 | 163.24 | 15.930 | ** | ** |
| | Min | 125.90 | 154.19 | 95.73 | — | 93.96 | 9.166 | ** | ** |
| 49 | Max | 212.89 | 226.15 | 212.02 | 202.15 | 213.30 | 20.810 | ** | ** |
| | Mean | 183.53 | 196.24 | 170.23 | 164.68 | 178.67 | 17.430 | ** | ** |
| | Min | 128.82 | 154.19 | 98.91 | — | 95.48 | 9.315 | ** | ** |

(Continued)

* Minimum velocities were in error.

** Air vent 2 acts as a piezometer during operation of low-flow valve.

Table 12 (Concluded)

| Test No. | Item | AV1A fps | AV1B fps | AV1C fps | AV1D fps | Ave fps | $R_e$ x $10^6$ | AV2 fps | $R_e$ x $10^6$ |
|---|---|---|---|---|---|---|---|---|---|
| 52 | Max | 124.40 | 140.32 | 122.91 | 118.29 | 126.48 | 12.340 | ** | ** |
| | Mean | 101.38 | 122.41 | 93.77 | 89.02 | 101.64 | 9.916 | ** | ** |
| | Min | 70.38 | 104.39 | 52.19 | 50.99 | 69.24 | 6.755 | ** | ** |

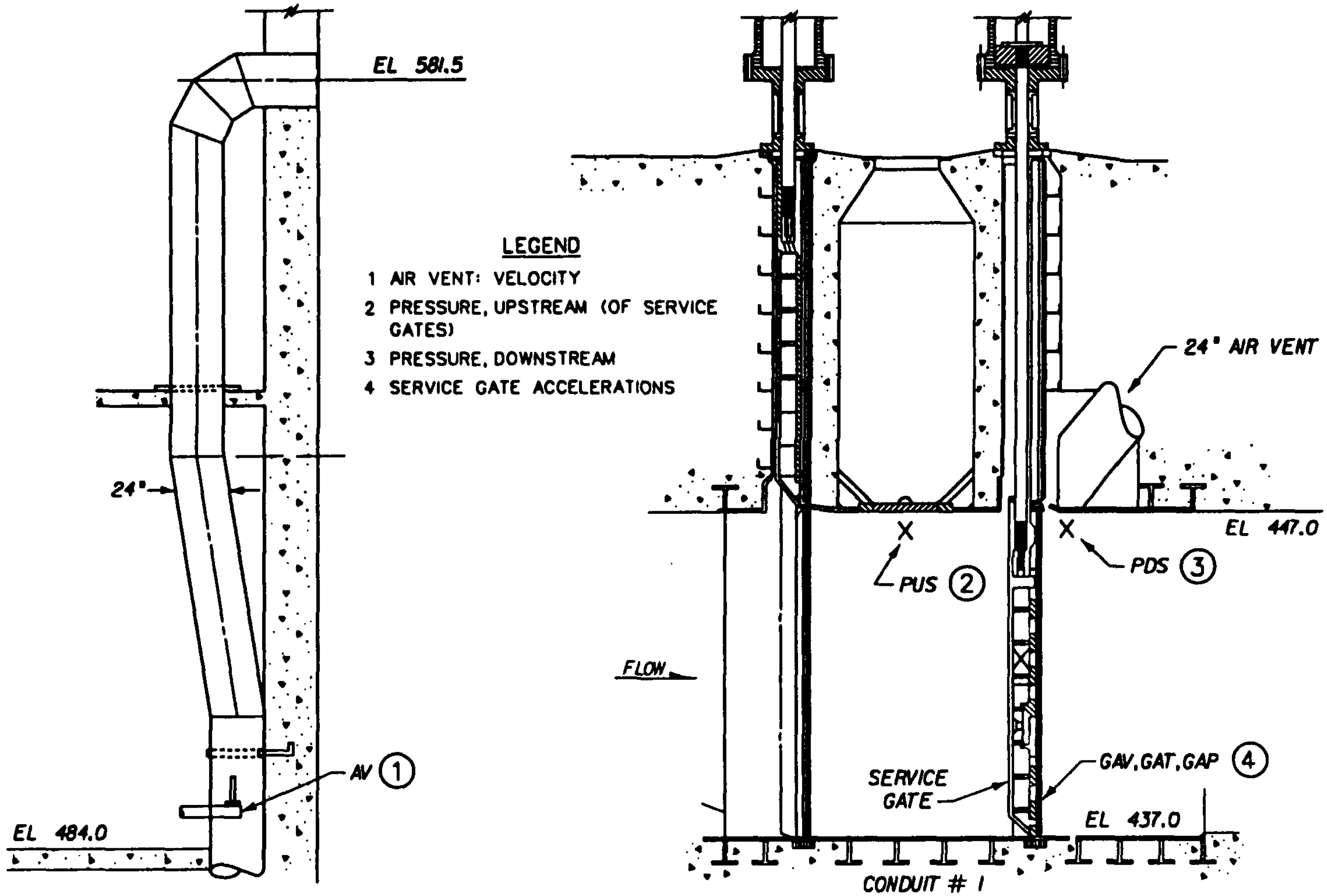
** Air vent 2 acts as a piezometer during operation of low-flow valve.

Table 13

Air Discharge

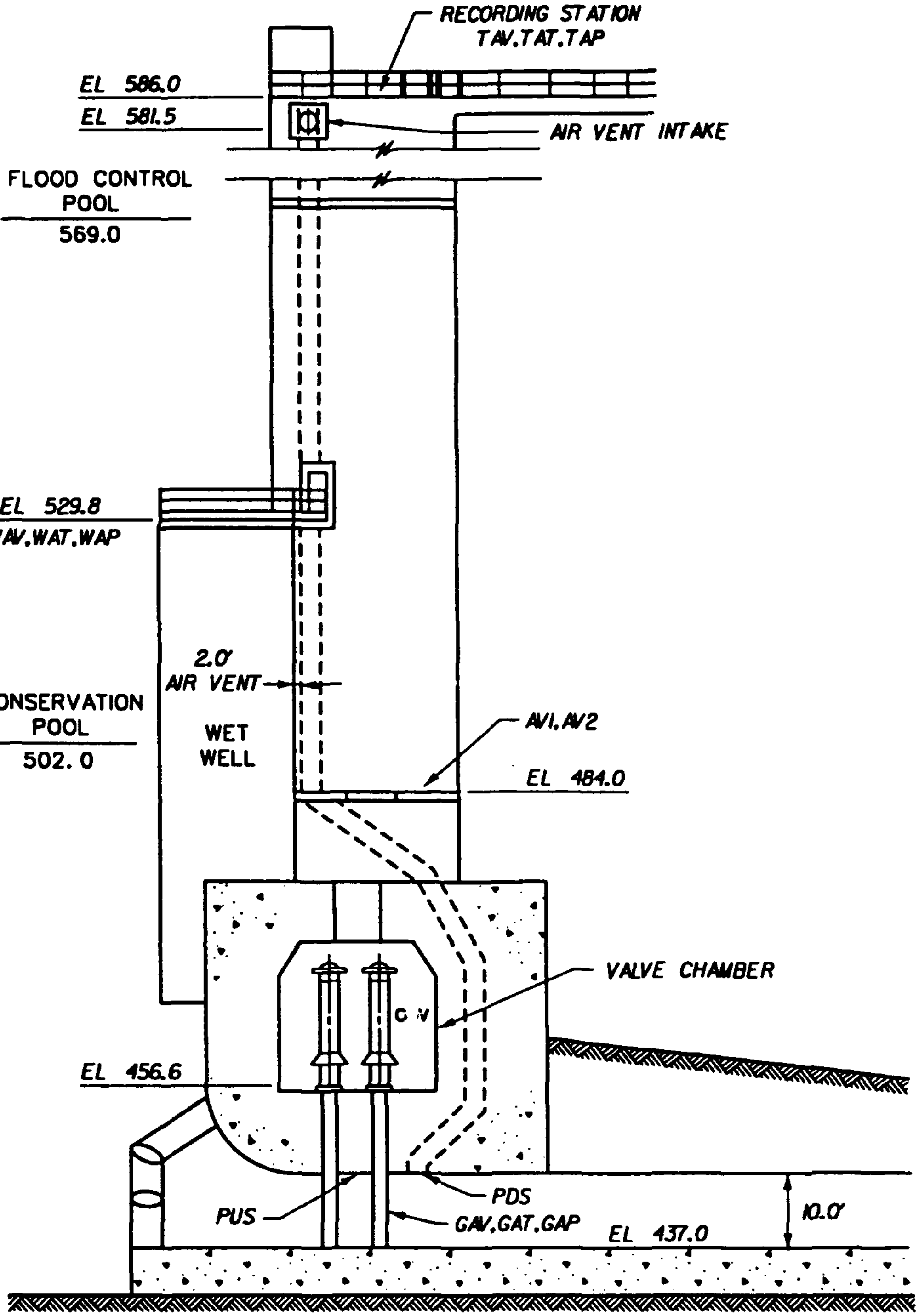
| Test No. | AV1 Max cfs | AV1 Mean cfs | AV1 Min cfs | AV1 Freq cps | AV2 Max cfs | AV2 Mean cfs | AV2 Min cfs | AV2 Freq cfs |
|---|---|---|---|---|---|---|---|---|
| 12 | 292.23 | 218.84 | 103.14 | 0.5 | 34.97 | 34.97 | 34.97 | 0.5 |
| 13 | 373.09 | 272.72 | 49.73 | 0.5 | 349.60 | 288.27 | 206.81 | 0.5 |
| 17 | 498.29 | 392.60 | 253.97 | 0.5 | 520.88 | 429.58 | 335.33 | 0.5 |
| 20 | 413.43 | 329.68 | 234.90 | 0.5 | 400.14 | 338.95 | 266.25 | 0.5 |
| 31 | 670.10 | 617.64 | 405.23 | 0.5 | 652.16 | 645.57 | 518.55 | 0.5 |
| 36 | 670.10 | 567.03 | 367.94 | 0.5 | 652.16 | 621.47 | 444.97 | 0.5 |
| 38 | 670.10 | 592.06 | 401.15 | 0.5 | 652.16 | 638.91 | 462.47 | 0.5 |
| 45 | 472.37 | 361.09 | 235.81 | 0.5 | 484.40 | 390.85 | 294.59 | 0.5 |
| 47 | 598.63 | 560.99 | 375.99 | 0.5 | 652.16 | 591.22 | 451.79 | ** |
| 48 | 646.29 | 512.83 | 295.18 | 0.5 | ** | ** | ** | ** |
| 49 | 670.10 | 561.31 | 299.96 | 0.5 | ** | ** | ** | ** |
| 52 | 397.35 | 319.31 | 217.52 | 0.5 | ** | ** | ** | ** |

** Air vent 2 acts as a piezometer during operation of low-flow valve.



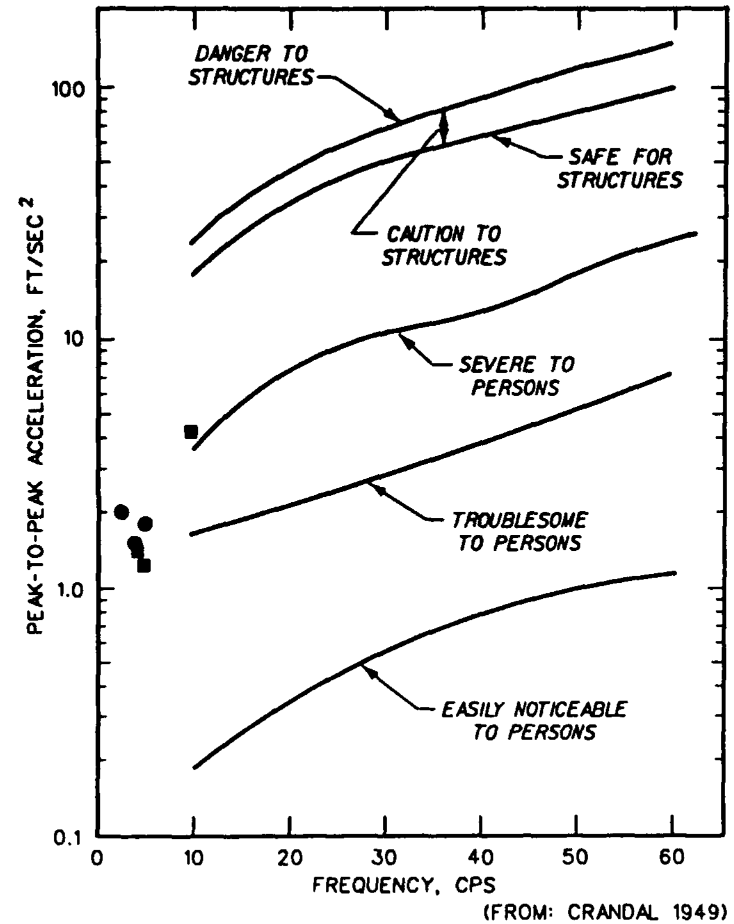

SECTION

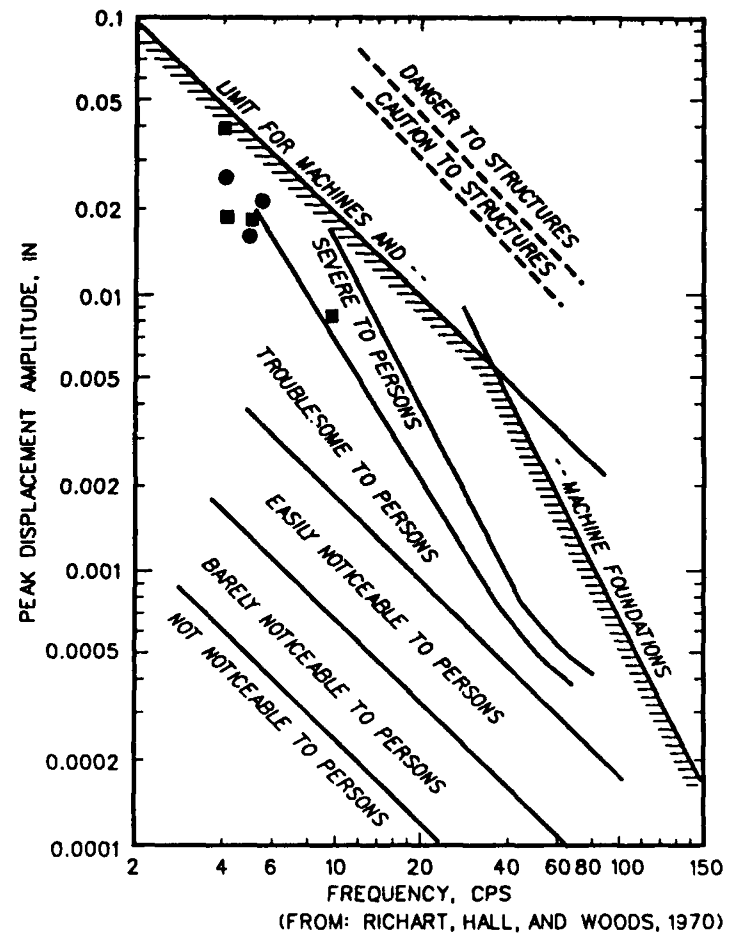
GILLHAM DAM
INSTRUMENTATION LOCATIONS




GILLHAM DAM
CROSS SECTION AND TRANSDUCER
LOCATIONS

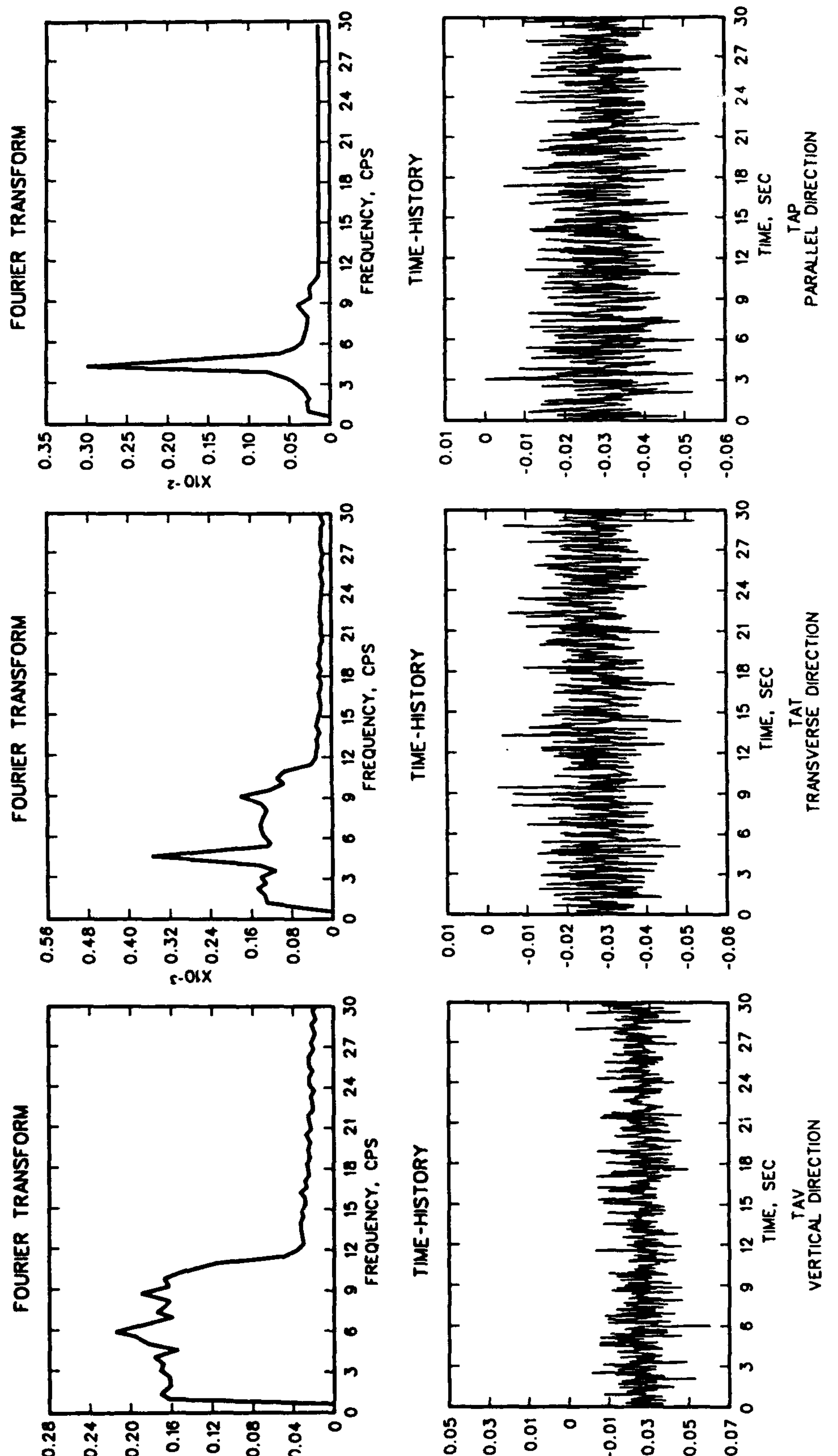
PLATE 2



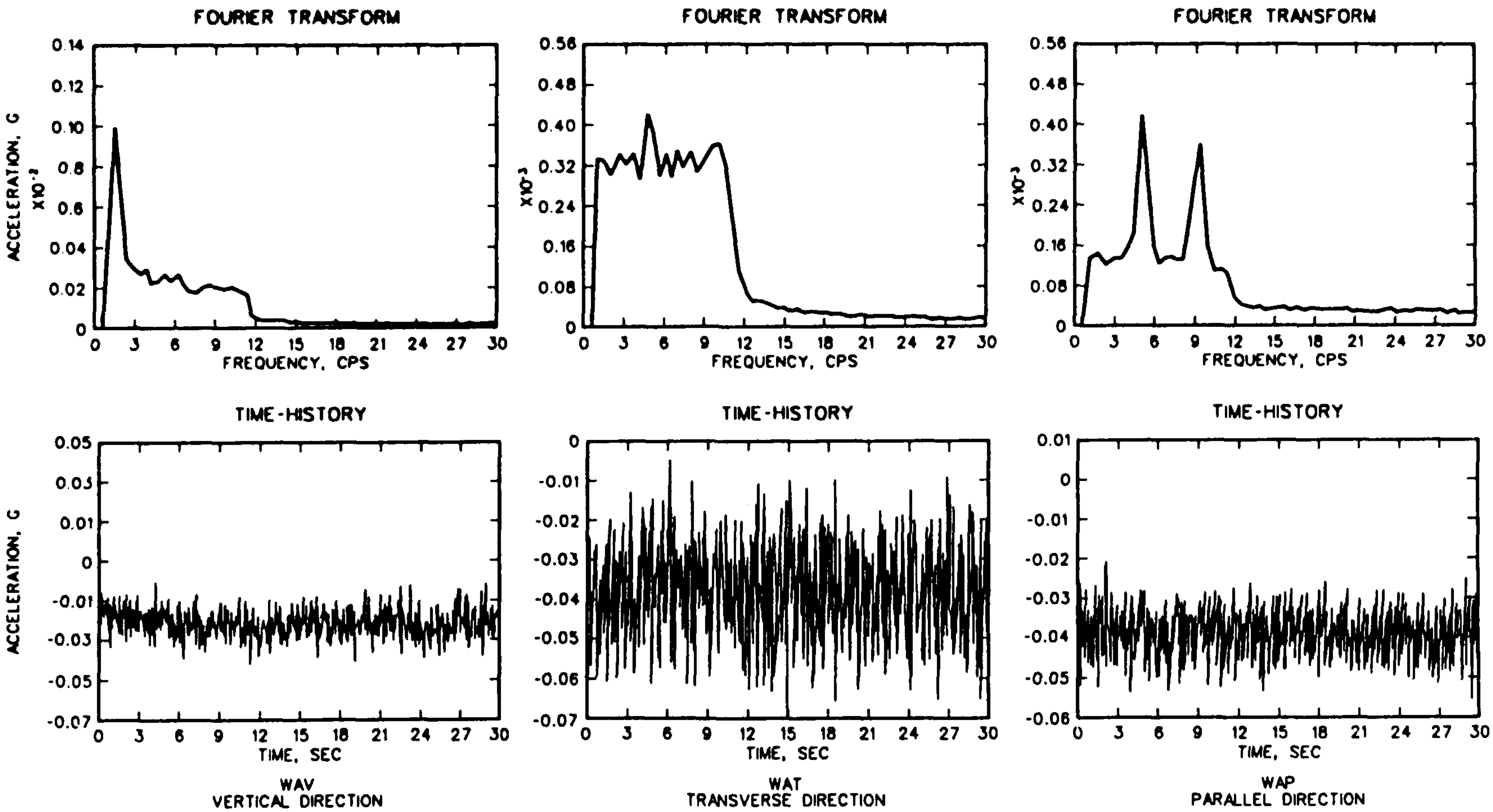

LEGEND
- ● INTAKE TOWER
- ■ WET WELL

## GILLHAM DAM
INTAKE TOWER AND WET WELL
ACCELERATION AND
DISPLCEMENT

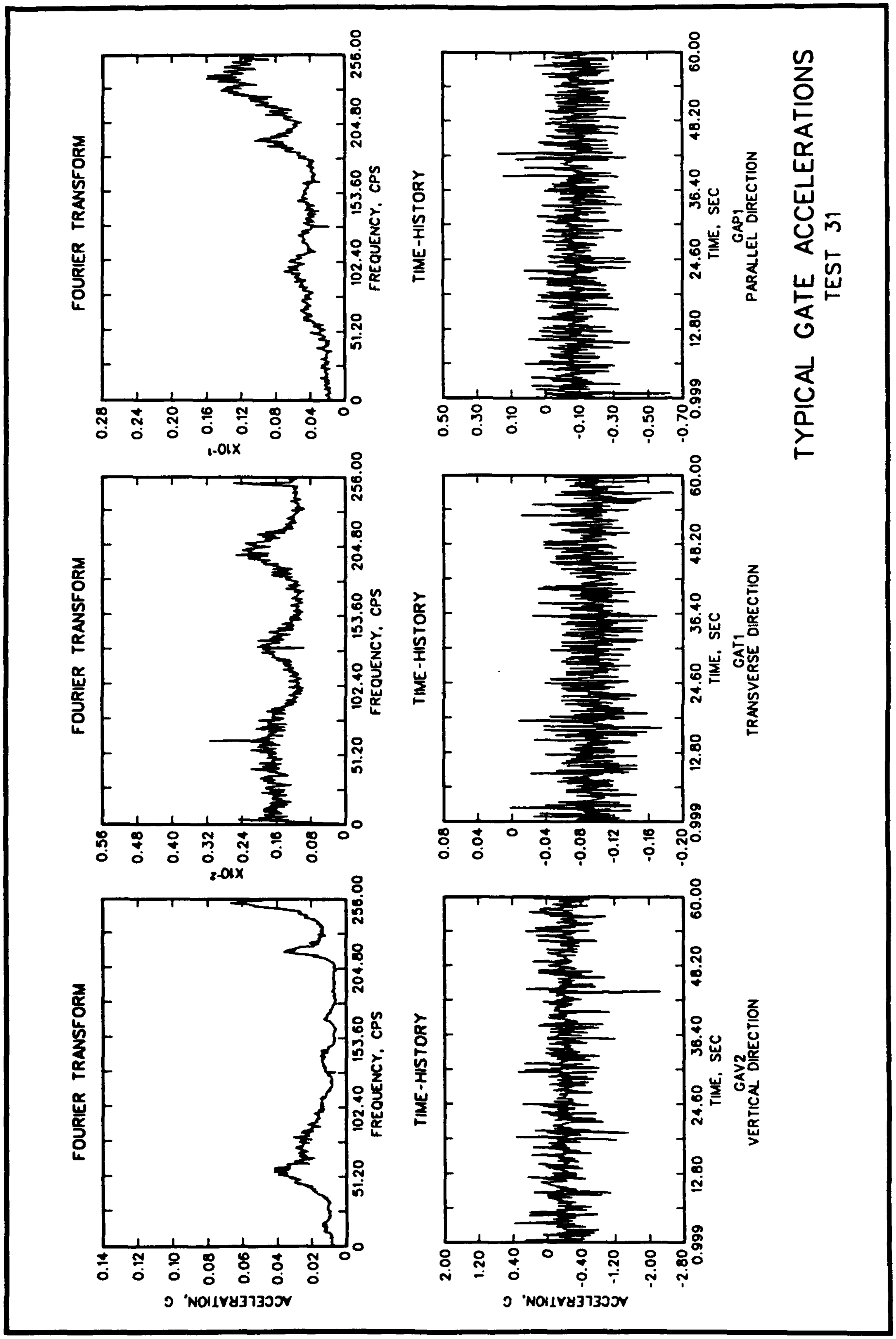



INTAKE TOWER ACCELERATIONS
TEST 31

PLATE 4

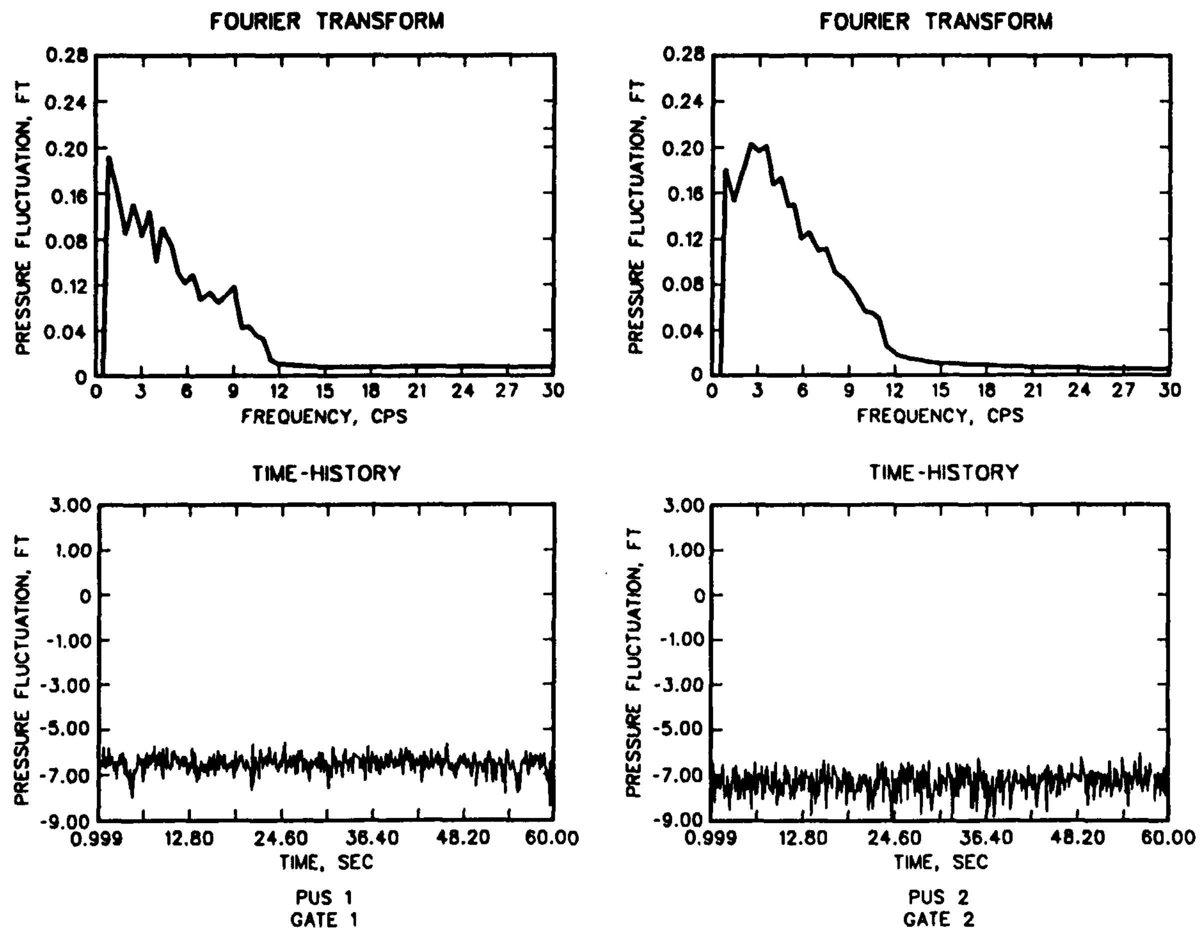



# WET WELL ACCELERATIONS
TEST 31

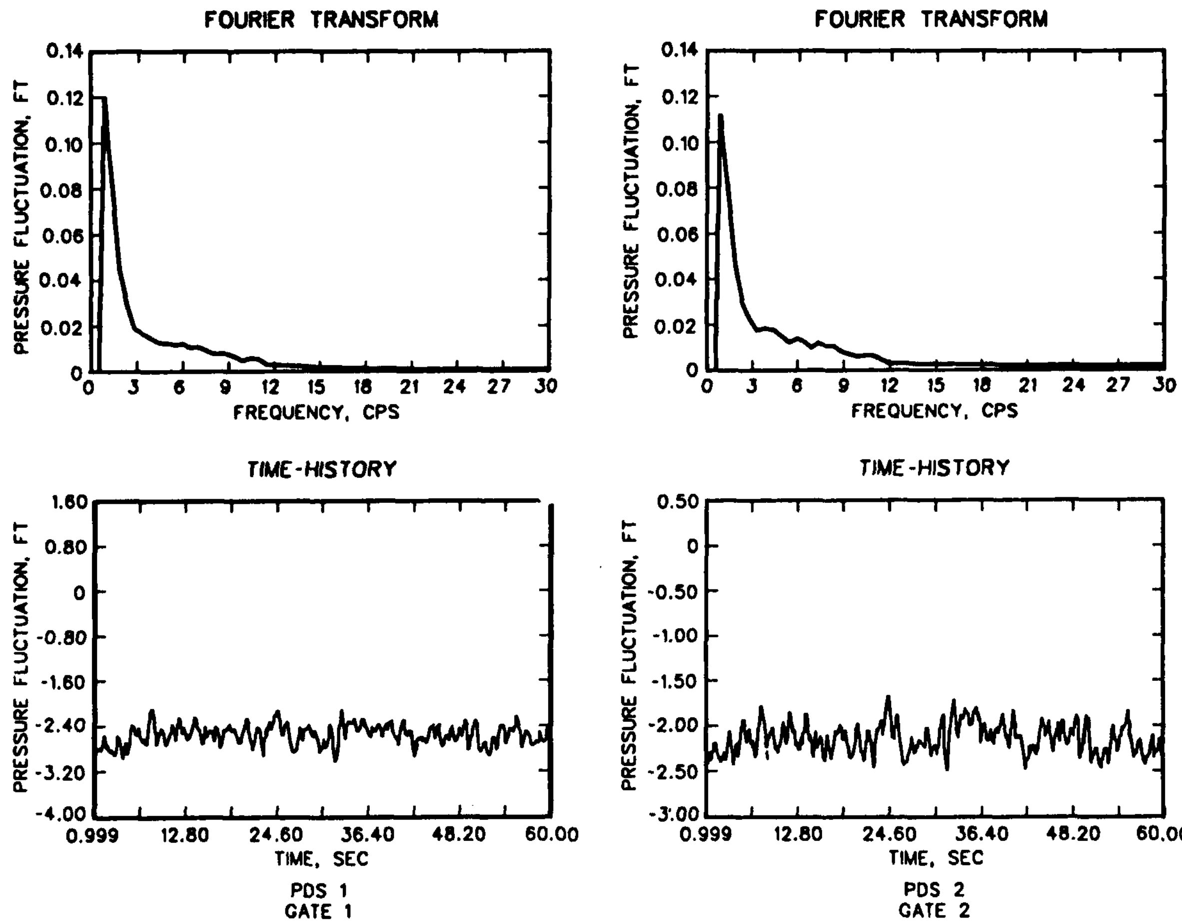


TYPICAL GATE ACCELERATIONS
TEST 31
FOURIER TRANSFORM
TIME-HISTORY
ACCELERATION, G
FREQUENCY, CPS
TIME, SEC
X10⁻²
X10⁻¹
GAV2
VERTICAL DIRECTION
GAT1
TRANSVERSE DIRECTION
GAP1
PARALLEL DIRECTION

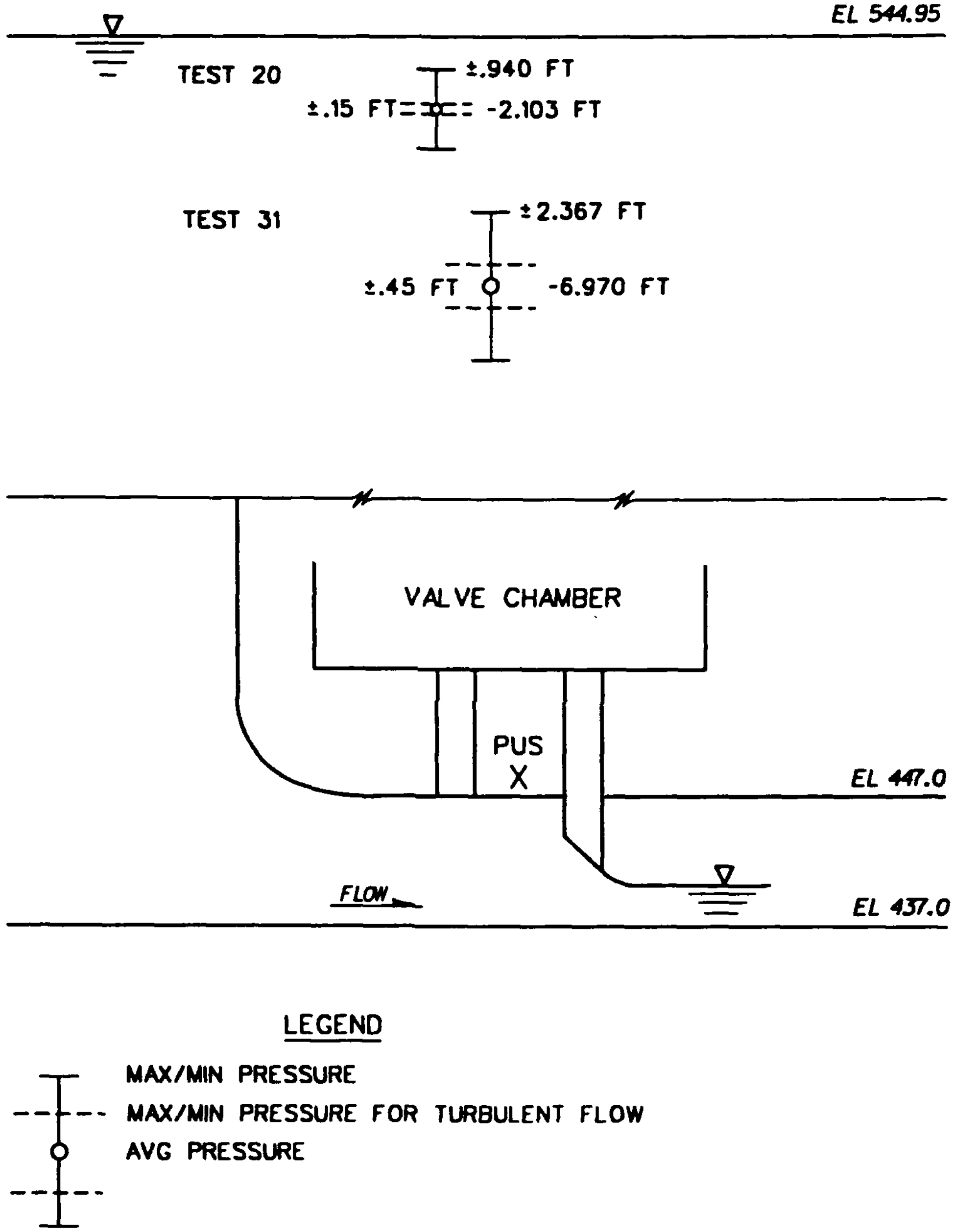

PLATE 6



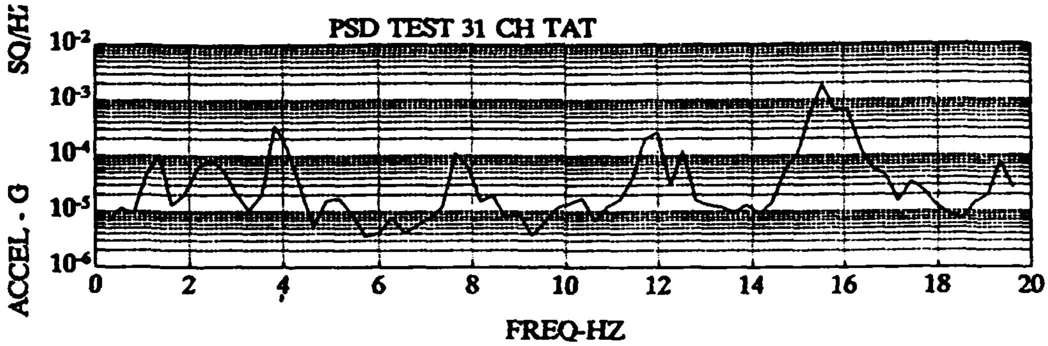

UPSTREAM
PRESSURE FLUCTUATIONS
TEST 31

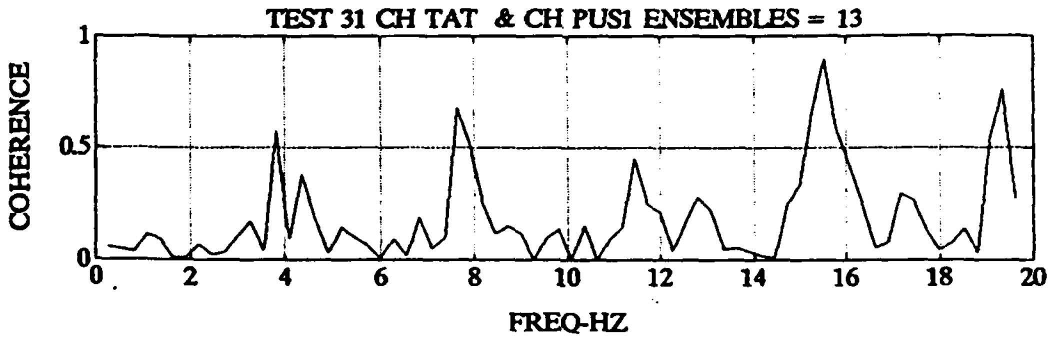


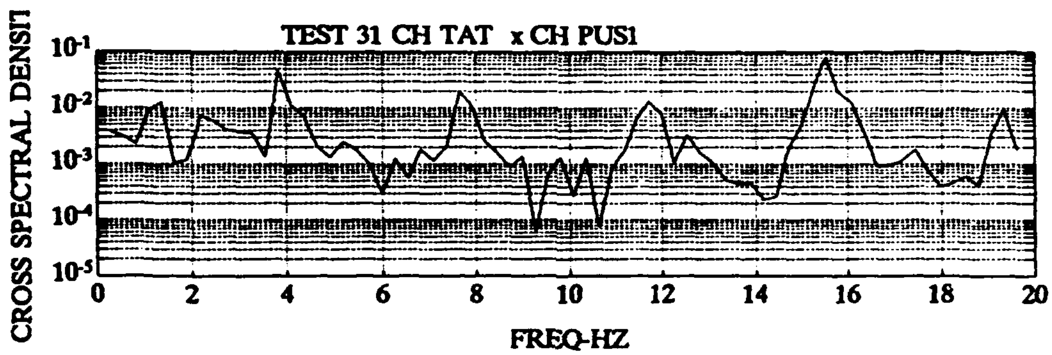

DOWNSTREAM
PRESSURE FLUCTUATIONS
TEST 31




MAXIMUM
PEAK-TO-PEAK PRESSURE
FLUCTUATIONS IN RELATION TO
NORMAL PRESSURE FLUCTUATIONS
FOR TURBULENT FLOW

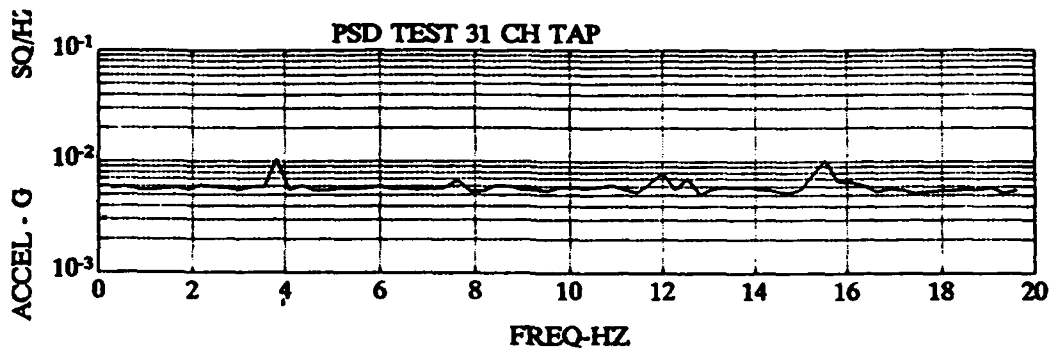


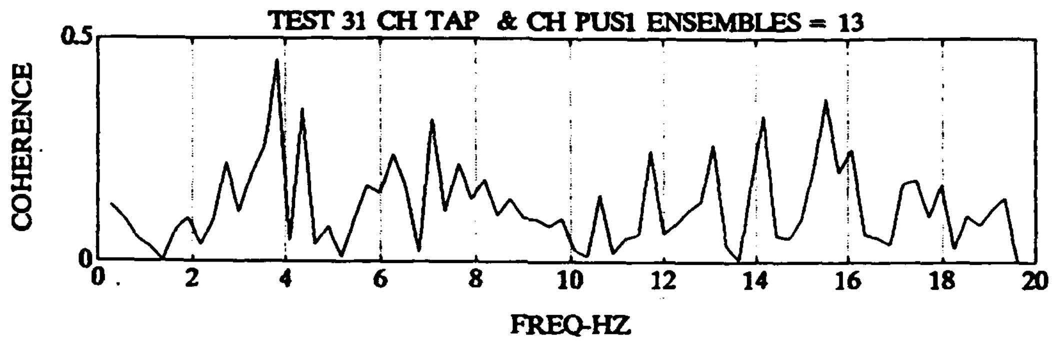



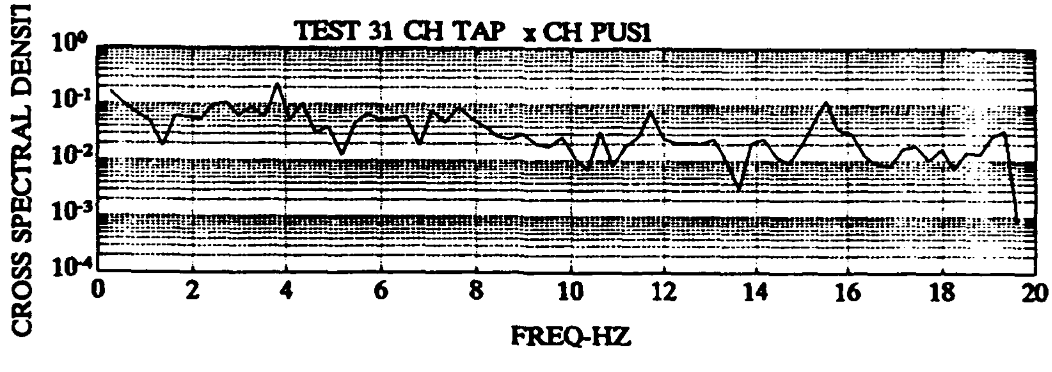




SPECTRAL DENSITY PLOTS
CHANNELS TAT AND PUS1
TEST 31

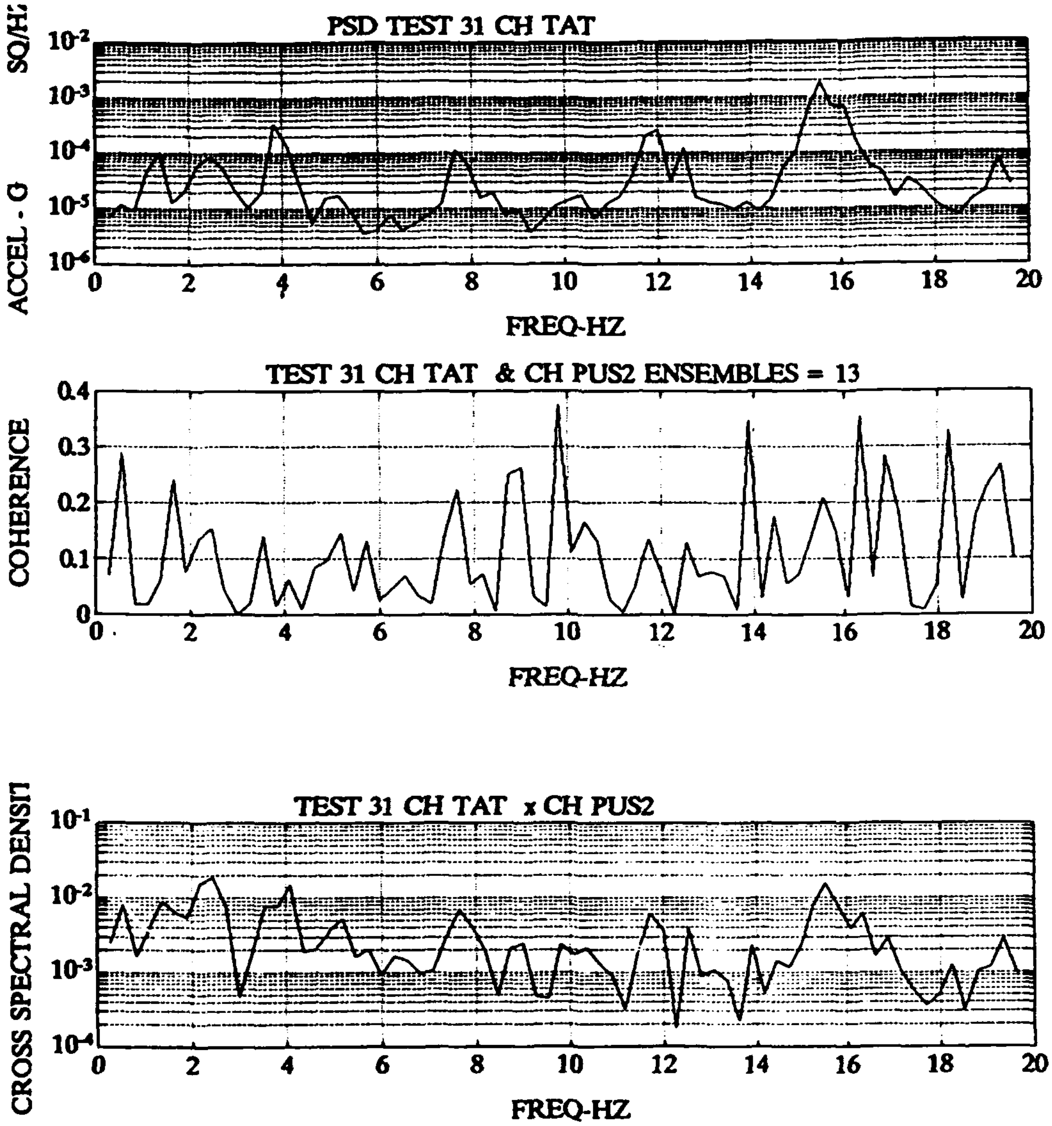
PLATE 10



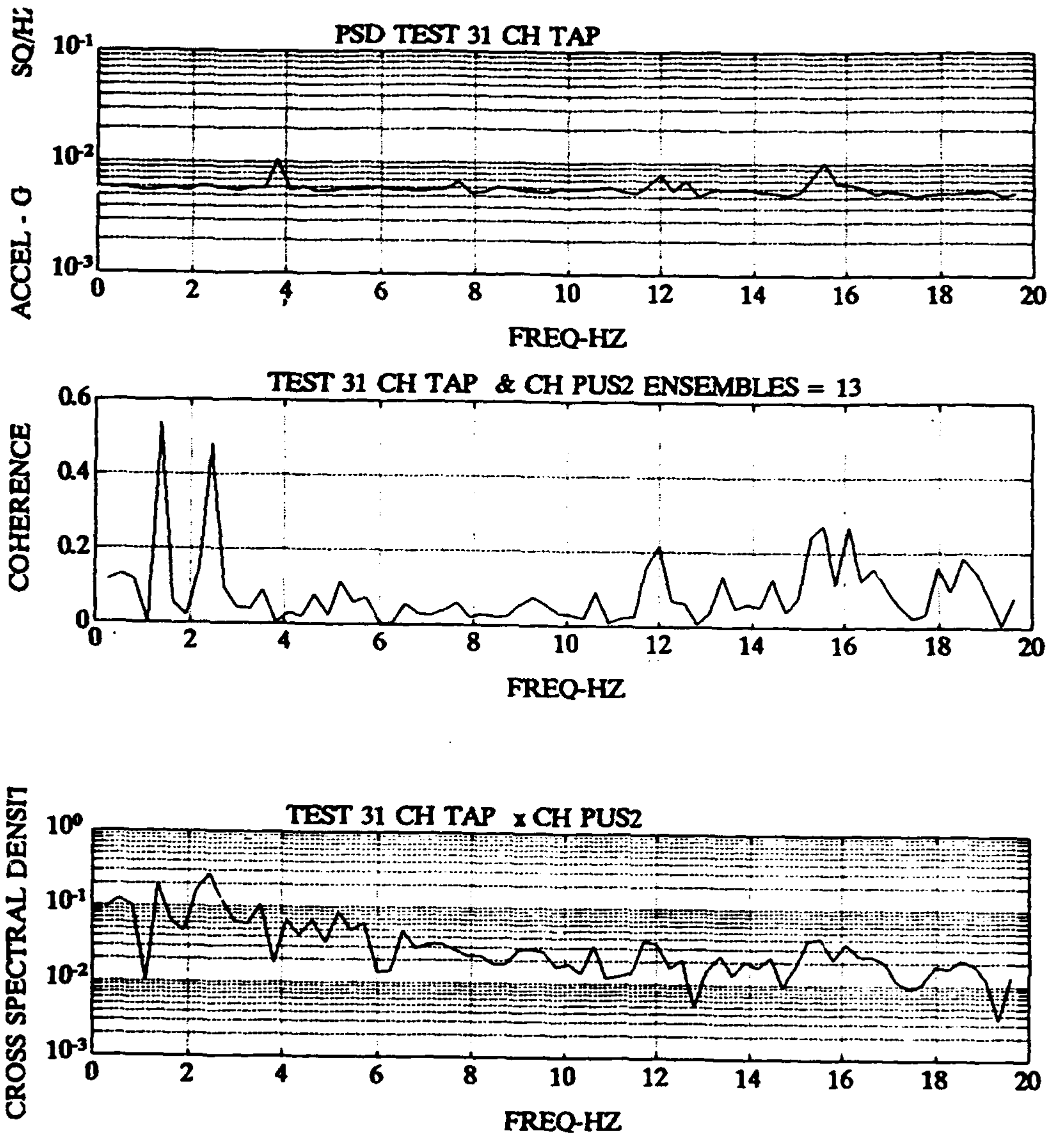




SPECTRAL DENSITY PLOTS
CHANNELS TAP AND PUS1
TEST 31

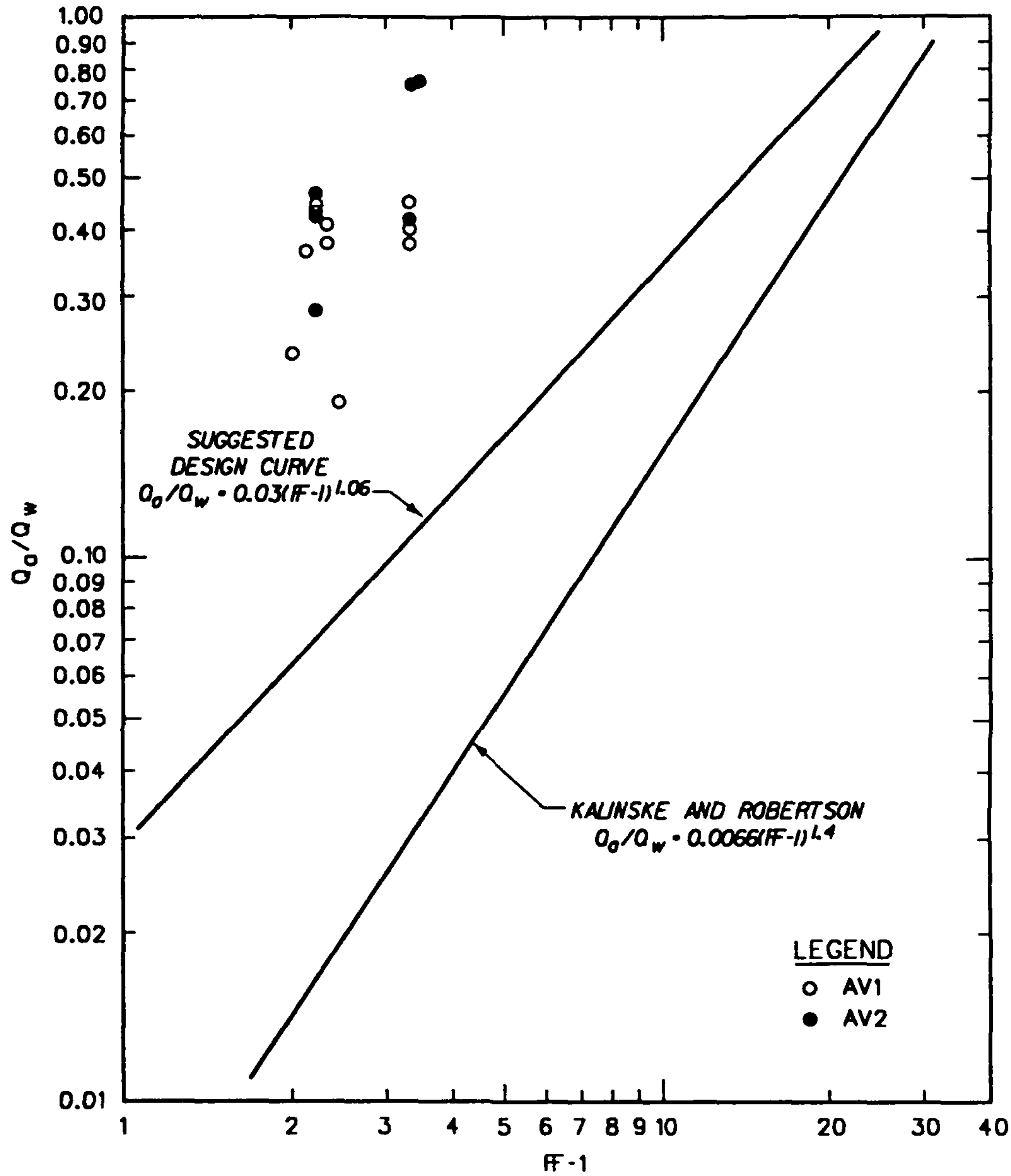



SPECTRAL DENSITY PLOTS
CHANNELS TAT AND PUS2
TEST 31

PLATE 12

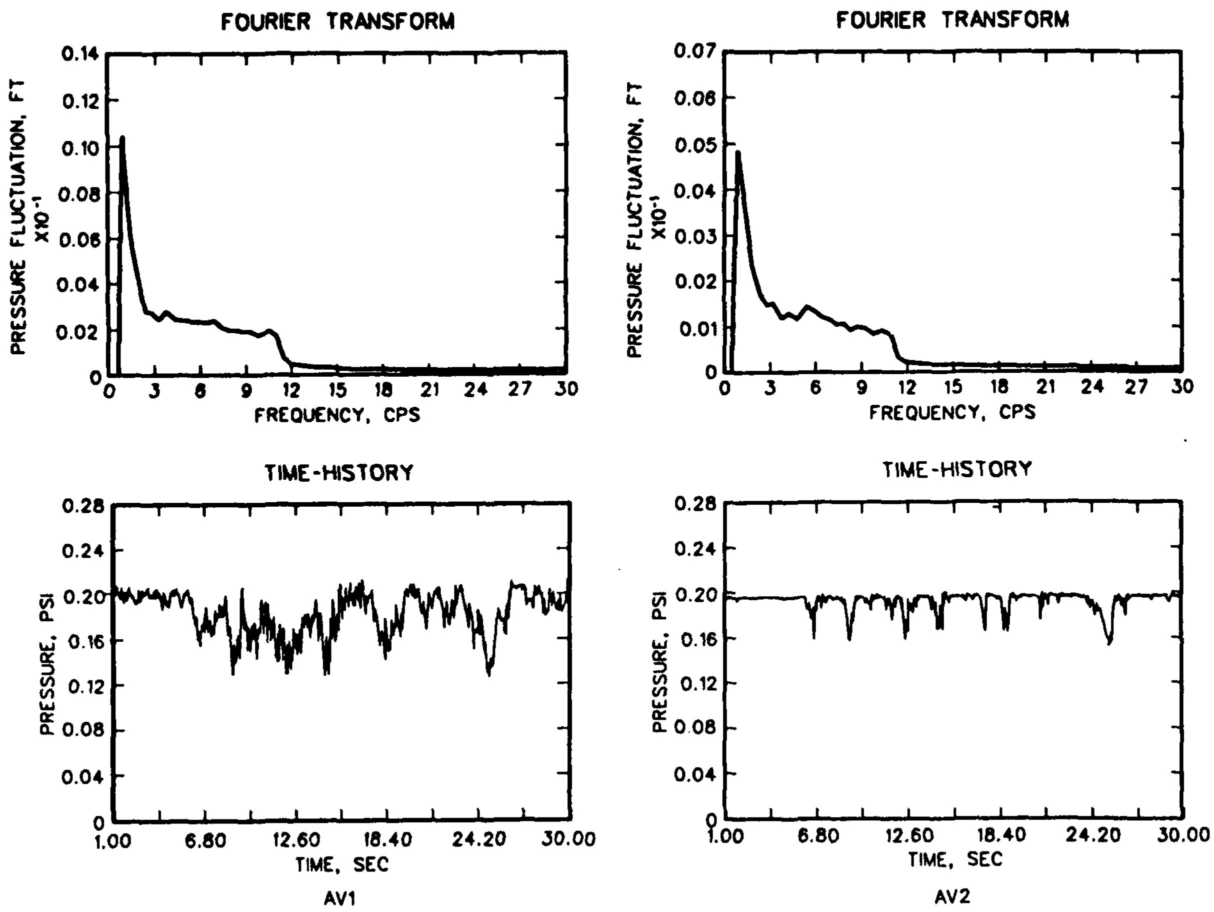



SPECTRAL DENSITY PLOTS
CHANNELS TAP AND PUS2
TEST 31




AIR DEMAND
FROM HDC 050-1

PLATE 14




DIFFERIENTIAL
AIR-VENT PRESSURES
TEST 31

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